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The magazine *for*, *by*, and *about* telescope makers! **Spring 1988**

Telescope Making

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Editor: Richard Berry
Associate Editor: Robert E. Cox
Managing Editor: Stephen Cole

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In this issue...

2 Editorial

3 Letters

4 Testing Paraboloidal Mirrors
by Dick Suiter

20 Astrofest 1987
by Robert E. Cox

28 A Replica of Galileo's Telescope
by Cecil O. Huey, Jr.

30 Home-Made Portable Observatory
by Ernie Williams

32 An Adjustable Chair for Observers
by John J. Shelley

36 A Sturdy, Low-Cost Wood Tripod
by Walter R. Coggan

38 Folding Refractors for Portability
by Robert E. Cox

42 The Blue Pages

Cover: "Summer Stargazing," composite photo by Harlan Creighton and Richard Berry

Editorial

No area of telescope making has frustrated amateur astronomers as much as mirror testing. In this issue, Dick Suiter explains the mathematical procedures behind zonal testing more fully than I have seen before. In the familiar context of Texereau's treatment of zonal testing, he shows step-by-step how to convert those funny little numbers into a wave-rating for your mirror.

Two conditions must be satisfied simultaneously, conditions recognized at least fifty years ago by Danjon and Couder. Why has this essential information eluded the English-speaking amateur for half a century? Perhaps it's because there is no English translation of *Lunettes et Telescopes*. Or maybe it's time we learned to read French.

We've rounded out *TM#32* with some good get-ready-for-summer projects—John Shelley's adjustable observing chair, Ernie Williams' portable observatory, Walter Coggan's sturdy tripod for portable scopes, and Cecil Huey's Galilean refractor. Enjoy.

The impact of better desktop publishing software is evident in this issue of *TM*. I'm now using Ready, Set, Go! 4.0. It's great—and I'm delighted to have justified type. (RSG3.0 just couldn't hack it.) Hyphenation, too!

TM#33 will be in the mail on June 22, and will carry an up-to-date report on RTMC. Hope I see you there.

—Richard Berry

Letters

Perfection Too Much?

Dear Mr. Berry/ I applaud articles like the "Optical Experts at the TSP" in *TM#31* and hope more are forthcoming. The amateur astronomer should have an understanding of superior optical systems. However, this article could be misleading.

Gregory's FK52/SK16 doublet seemed to win the contest. Fine, but let's think about this lens. Is this the best you could do? To correct this doublet for spherical aberration, spherical surfaces are not enough, the lens must be aspherized. This is difficult, even Gregory (who is an accomplished optician) has not finished aspherizing this lens (although he's had this lens a long time). Could this lens be sold to the amateur? At what price? FK52 or FK01 is not cheap and what grade of glass would you buy?

There are other problems with fluor glasses such as temperature variation (cell and cool down time), sensitivity to atmospheric attack and workability. This is not to say the lens should not be used in some applications. But let's make very clear all of the problems.

If Gregory wants to make the perfect telescope, why doesn't he make a fluorite doublet with the purest FK01 and ZK9, multicoat all air-to-glass surfaces, or make a fluorite triplet (*Applied Optics*, February 1962, Vol. 2, No. 2, p. 127-128, for example) and put either lens in an oversized redundantly baffled straight tube f/15 or slower. But let's get back to practicality.

Roland Christen makes apochromats and sells them. These lenses may not have the ultimate color correction of the above but they are affordable and are not temperature sensitive! This is very important. Have you ever waited for a Quantum 6 or 8 or a Questar 7 or 12 to settle down on a cold winter night in northern Ohio? Forget it! Roland's glasses are coated and do not require an aspheric surface to correct for spherical aberration. His f/12 lens is very smooth: no zones.

I feel that his scopes got shortchanged in the comparison—let's remember the lack of problems with these lenses and the aperture difference. Mr. Christen is working on a 8" f/15 triplet. When it become available, let's compare color, definition, thermal properties, contrast, cost, and all other relevant factors for the proper perspective.

Thomas Back
370 Twilight Drive
Seven Hills, OH 44131

Fluorite Costly, Sensitive

Dear Mr. Berry/ Thank you for a most interesting report on last year's Texas Star Party. Unfortunately, for me it was a very disturbing report. Mr. Buchroeder's comments regarding commercial apochromatic lenses (Astro-Physics, Tele-Vue, and Vernonscope) is very unfair to say the least. It is true that the theoretical color correction of closely spaced triplets is not perfect, but when compared to achromats, there is no contest. To totally dismiss this technology as irrelevant and unimportant does a disservice to the amateur community. There are certain practical aspects that cannot be ignored. Let me put some of these in perspective.

At Astro-Physics, we have been actively developing apochromatic lenses for about 10 years. We were not totally unaware of fluoride, in fact our first designs used fluoride materials (Schott FK51 and crystalline calcium fluoride). These designs were judged impractical for the following reasons: 1.) Fluoride glasses are very expensive. 2.) The materials are very brittle and have no mechanical strength. They are easily chipped and damaged during normal handling. 3.) The high thermal expansion of the glass combined with susceptible to cracking if not handled properly. 4.) The final product must be treated with the utmost care by the amateur to prevent destruction.

While cost has steadily decreased, the material is still far from cheap. Items 2 and 3 can be overcome by the development of proper production techniques. Our experience has been that fluoride materials can be worked in a production setting, and of course the Japanese are doing it almost routinely now. In fact, fluoride doublets are easier for us to produce than triplet apos. The only problem then is item #4: fluoride can be damaged in several ways in the field.

Thermal shock will cause the material to crack in two. This can happen when a telescope is taken from a warm room or car into the freezing night air. I have heard a number of reports of small Japanese fluoride refractors meeting their doom in this way. A more subtle destruction can occur over time. Mechanical vibration produces small cracks at the edges of the lens. These will then propagate across the disc when the lens is subject to repeated temperature cycling. These problems may or may not be rectified in the future by the glass manufacturers. Until that happens, I would advise caution against relying on this material as the mainstay of modern refractors.

I have a few comments on the Gregory doublet. It is, of course, the fluoride material that provides the design with its excellent color correction. The large airspace eliminates the sphero-chromatism which is present in all closely spaced lenses. However, the large airspace combined with the extreme internal curvature causes other problems. The lens must be aspherized to remove the resultant spherical aberration. While this can be done by an expert optician, aspheric surfaces cannot be readily reproduced in a production setting. This design then fits the bill for an amateur who has lots of time to figure and aspherize, but it would be a disaster to opticians who must produce many lenses in a given amount of time in order to put food on the table and pay the bills. Lenses that require no aspheres are not only easier to produce, they also invariably have smoother surfaces for a cleaner, tighter image.

The extreme internal curvature means that the lens is very subject to temperature effects. I have seen lenses like this that take five to six hours to produce a reasonable image. The more conventional Japanese doublets that use KzF2 as the flint element have much shallower internal curvatures. Even though this does not produce the perfect color correction of the Gregory FK01/SK16 combination, the end result is a much more practical lens with little or no visible color error. The 4" fluoride that Buchroeder looked through even had the expert fooled. My own experiments with FK01/KzF2 show that an f/15 lens has almost no measurable color error over the visual spectrum.

Lastly, there is the matter of economics. A Gregory doublet in production would cost between $10,000 and $15,000 to produce. There are a number of realities that makes this high price necessary. Besides the labor time required to produce a perfect specimen (anything less would not do justice to the design),

Testing Paraboloidal Mirrors

What Every Telescope Maker Should Know About Testing Telescope Optics

by Dick Suiter

Introduction

You have never made a mirror. "Testing mirrors is for crazoid mirror makers," you say. "It's not for me." You decided long ago that mirror-making was one can of worms you would not open.

Besides, you argue, why concentrate on the optics when all the fun is in the mechanical design? Aren't commercial mirrors of reasonable quality available at very good prices?

So who should test mirrors? Nobody—right?

Wrong. Testing mirrors is for everyone. Even if you never plan to make a mirror, you should be skilled at testing them. You owe it to yourself to become an intelligent consumer. Commercial telescope makers have never, by and large, been a very principled crowd and the situation appears to be getting worse instead of better.

At one end of the spectrum, advertising copy states optical quality in tricky ways. At the other end it comes down to bald-faced lying. In the day and age when a major Schmidt-Cassegrain manufacturer euphemistically calls the production of awful telescopes "a quality-control problem," we had better learn how to test telescopes.

The most generous way of interpreting the production of bad Newtonian telescope mirrors is saying that tolerances appear to be set too large. If you get a mirror at the center of the tolerance, you will be pleased. If you get a mirror at the edge of the tolerance or one just close enough to squeak by, you will be disappointed.

I have seen mirrors that would not pass even a glance at the Foucault shadows. Although I find it incredible (because they're dealing with such a difficult to control material as polishing pitch), I have come to the conclusion that some companies don't test all of their mirrors or perhaps test only one or two in a batch. This appears to be particularly true of small, long-focus mirrors, where companies could possibly have a chance of getting away with it, but I have even found it in quite large mirrors.

To their credit, once you return bad mirrors to manufacturers, they generally agree to replace them. The worst manufacturers can do to you is be condescending: "Well, our tests are certainly much better than yours, but we want our customers to be pleased, so we'll unconditionally replace the mirror." An acceptable mirror always follows this.

The most honesty I ever saw was when one company admitted it had blown the test because the null tester had been set wrong. The replacement mirror was a good one. One other manufacturer refused to admit there was anything wrong with a diagonal that showed significant astigmatism. This company claimed to return it to us, but it was obviously not the same diagonal.

I suppose real perfectionists could actually exasperate a manufacturer enough to receive their money back with a note to "go elsewhere," but I've never had to return a mirror more than once. Of course, I've tempered my testing with a realistic attitude about the characteristics of what I'm buying and how much I'm paying. If I'm getting a dirt cheap price, I don't demand perfection.

In this article I will describe my system of testing, including some new techniques. These instructions are not meant to stand alone. Get a good mirror-making book and read it as a preamble to what appears below. I do not want to reiterate what has been said well before. What I want to do is clarify and bring together some widely separated and often misunderstood instructions. I also want to give my perspective on the process of testing and present some variations on test reduction methods.

The Methods Available

The Star Test. The simplest way to test a mirror is with the star test. This procedure is particularly useful for evaluating finished optics. However, the star test is often too sensitive: unless it is perfect, your mirror will fail the star test in some fashion. It is up to you to determine if it fails severely enough to be rejected.

If your mirror performs well in the star test, you may thereafter use it with confidence. If the mirror doesn't perform well, then further testing is necessary. You must become skilled in interpreting the star test to determine exactly what is at fault.

A problem with using the star test is the precondition of the instrument's existence. Often you don't have the telescope completed when you want to test the mirror. Furthermore, you don't want to have the tube drilled for a mirror that will fail. Manufacturers have a predetermined range of acceptable focal lengths (usually ±3 percent), and if you have the telescope tube measured and drilled for a mirror on the lower part of this range, rejecting the mirror can lead to a replacement mirror on the upper part of the range. Either your focus extends to the upper end of the focus travel or you must move the mirror cell. Moving mirror cells is easy with conventional tube reflectors but is often difficult with tailgated Dobsonians. The ideal circumstance would be testing the mirror, at least provisionally, before you make cuts on the tube.

In the case of homemade mirrors I advise that you actually complete the telescope to star test with an uncoated mirror (after all, you're stuck with the blank). I think the star test is that important. It allows you to give a final adjustment to the figure, a last tweak. The test is brutally honest.

I once did the final figuring on a full-thickness 16-inch. When the Foucault test said the mirror was finished, the star test said there was a small distance yet to go. I finished the figuring according to what the star test said. That mirror seldom witnesses good enough seeing to deliver full-resolution images, but when it does, the images are like riding aboard *Voyager*. I once saw it give a roughly 1/3-arcsecond view of Jupiter—a moon was crossing the planet's disk at the time. It cast a shadow so crisp-edged and sharp it looked as if someone had punched a hole in the planet. The amount of detail I saw on the planet would have taken hours to draw. That mirror is not perfect. It has a small amount of astigmatism, a slight turned edge, and a small but noticeable amount of surface roughness. Even so, the performance of that 16-inch has made many owners want to go home and kick their large commercial telescopes.

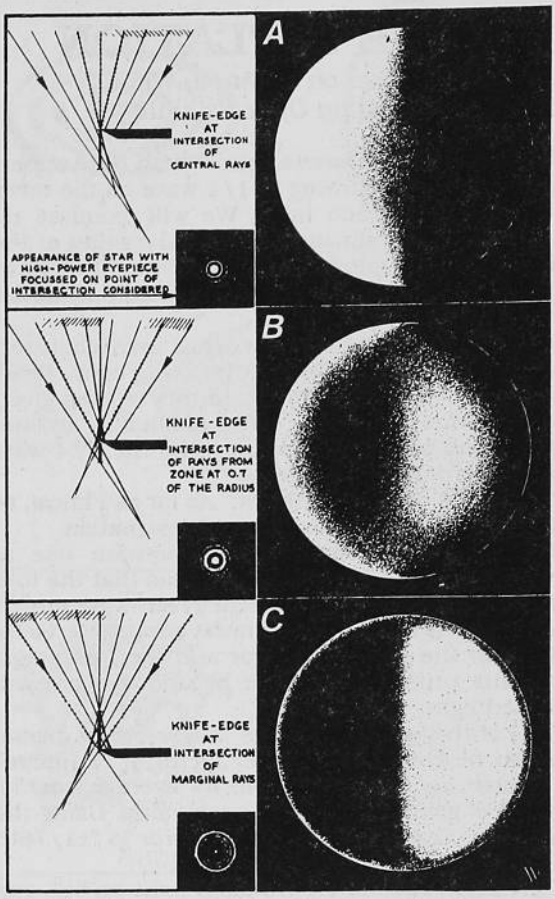
Another problem with the star test is that it's not quantitative, at least in the version most people employ. The Hartmann test, a sort of quantitative star test where a mask is employed over the aperture, is seldom used by amateurs.

The Foucault Test. A problem with bench testing with the Foucault test is that few nonmirror makers have the necessary equipment or expertise. During the making of your first mirror, you have to build the Foucault tester, a vastly less difficult task than the mirror itself. Thus, making the tester is only a glitch on a larger project. You learn to read the shadows as your mirror changes shape. But if you are making a telescope with finished optics, making a tester seems to be a sidetrack you don't want to take. Once you have the tester completed, you have to learn with one example—your finished mirror.

But I'm going to ask you to make a tester anyway. It will prove more useful as you develop skill in interpreting the shadows. Perhaps you won't trust your evaluation on the first mirror, but after you have seen many mirrors, your confidence will grow. And, once it's made, you have the tester forever. A club or group might make only one.

Making testers is no longer quite the chore it once was. You can make a kinematic stage riding on Teflon according to the directions in my article in *TM#22* or in Richard Berry's book, *Build Your Own Telescope.* You can make a Foucault tester head using the Mini-Mag flashlight bulb and the directions in Gil Stacy's article in *TM#30.* All of these instructions require only woodworking tools and experience, maybe with the exception that you have to drill holes in metal.

It used to be that testers were made in only one form. The light source, being tied to a wall socket, did not travel on the platform. Such testers are called FIXED SOURCE testers, and they feature a natural doubling of the zonal measurements because they measure an average between two locations, one of which is fixed. This type of tester became so ubiquitous that people wrote the testing procedures assuming this doubling. Simple, battery-powered testers with the source and knife mounted close together and moving together have become more popular now that people are figuring such fast mirrors.



Shadows in the Foucault Test

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How to Make a Telescope, 2nd Edition by Jean Texereau,
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Self-aligning slitless testers make for less grief during testing. (Actually, the term "slitless" is a misnomer. I prefer to call them "one edge" or "divided knife" testers.) They will be self-aligning whether they have a slit or not. All testers use one side of the slit only as a mask to limit the amount of light that gets by.

These other testers are called MOVING SOURCE testers. They measure the differences in the center of curvature of the zones directly, which for a parabola measured in the Foucault test is the same as the sagitta, or r-squared/2R. (I'm using a very loose definition here. The actual center of curvature of the zones is not on-axis for a nonspherical mirror. It follows a complicated curve. What I'm calling the center of curvature is actually the on-axis focus of each annular zone.)

The trouble comes when you try to insert the values measured with a moving source tester into the fixed source formalism. I prefer to make my measurements consistent with the existing fixed source reduction methods by DOUBLING my moving source raw measurements at the very beginning. I then use the fixed source methods undisturbed.

I am not going to repeat instructions for making testers here. That is not the purpose of this article. Rather I am going to tell you how to go about testing your mirror in an organized fashion. I am writing this article in association with another by Robert Follett, who describes a considerably different procedure. Perhaps

WAVE INFLATION

A Primer on the Many Ways of Stating Optical Quality

Let's assume we have a mirror with pure spherical aberration amounting to 1/4-wave on the wavefront in yellow-green light. We will examine the multiple ways of stating the optical quality of this mirror. Most people have heard of the "1/4-wave" Rayleigh limit without knowing precisely what it is and how it is measured.

This lack of knowledge is what manufacturers ferociously exploit in their advertising copy. Readers tend to drop the qualifiers (if they're even given) and continue to compare the artificially inflated wave errors appearing below with the 1/4-wave Rayleigh criterion:

"1/4-wave on the wavefront." As far as I know, no manufacturer uses this accurate designation.

"1/8th-wave parabolic." In common use as recently as ten years ago. This means that the total phase delay of a surface with an 1/8th-wave error is 1/4 wavelength. The wave must propagate to the bottom of the 1/8-wave error and then propagate out. This puts it 1/4 wave behind the properly reflected light.

"±1/16th-wave parabolic." Some clever person realized he could get another factor of two merely by measuring the error from its average position instead of giving its peak-to-peak value. Using this definition, Texereau's example mirror is "±1/76th-wave parabolic."

"±1/20th-wave of He-Ne laser light on the surface." Not only does the test statement imply that the mirror was tested with a high-tech device like a laser (perhaps it was not) but the wavelength of He-Ne laser light is longer than yellow-green light, so the criterion is less stringent.

This represents the present state-of-the-art in wave inflation. But the unscrupulous optician can go even further. Perhaps we will see the following:

"1/27th-wave RMS surface mirrors." The RMS deviation is intended to measure statistical or periodic quantities of surface roughness, but there is no reason that the mathematics cannot be abused in this manner. By using He-Ne as a wavelength standard, someone trying to fool a buyer can assert his claim that a 1/4 wave of spherical aberration focused at the center of curvature of the 70 percent zone is 1/31-wave RMS.

Take all wavelength claims with a grain of salt. Believe only what YOUR eyes tell you. Remember, ALL of the examples given above are descriptions of the same 1/4-wave mirror.

you can pick and choose from the techniques you see here and from techniques you have already seen published and come up with a coherent system with which you feel comfortable.

The Star Test

This test, in some form, is as old as the Newtonian reflector. It was first incompletely described by John Hadley, who made the first astronomical Newtonian (oddly enough, the first instrument he so figured could have been safely left spherical). It was used off and on by various people, some of whom apparently viewed it as a trade secret, until it was fully described by H. Dennis Taylor in *The Adjustment and Testing of Telescope Objectives.*

Herschel was apparently not aware of this test, because he used a crude two-zoned method to test his mirrors. The Clarks, on the other hand, were certainly familiar with it. They built a huge underground tunnel so they would have undisturbed air for the test using an artificial star and an optical flat.

Some people confuse the star test with double star testing; that is, seeing how close together a double can get before they can't resolve it. While double-star splitting does give valuable information related to optical quality, it is far from the complete story. The unusual character of double stars—high contrast and one separation—often gives little information about other contrasts and separations that may be equally interesting. For example, Sidgwick noted in his book, *Amateur Astronomer's Handbook* (published by Enslow) that a fair amount of spherical aberration has little effect on resolving power near the limit of the instrument. But it has a severe effect on the low-contrast markings of planets. Another difficulty with double star evaluation (as with all in-focus tests) is that you are unable to trace the origin of optical difficulty even if you know of its existence.

The essential feature of the star test is that the image is slightly (emphasize the term "slightly") out of focus during the test, so there is some position information associated with the optical difficulty. You may still have to use some tricks to extract this information from the image, but at least you have a chance.

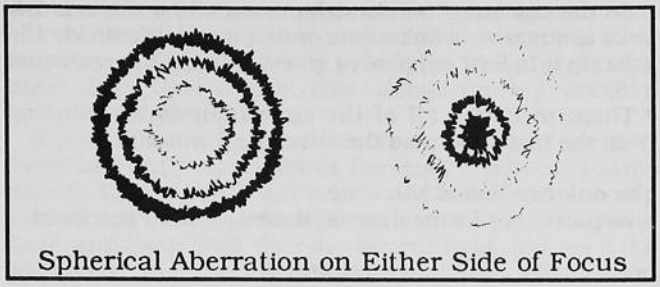
The most difficult thing about doing the star test is judging just when you have defocused it far enough. Some folks take it too far out of focus and then can't see any difficulty because the test loses sensitivity when done too far defocused. This is what you learn when doing the star test:

Focus	**Far Out**	**Slightly Out**	**In**
Sensitivity to Error	Low	Moderate	High
Sensitivity to Position	High	Moderate	Low

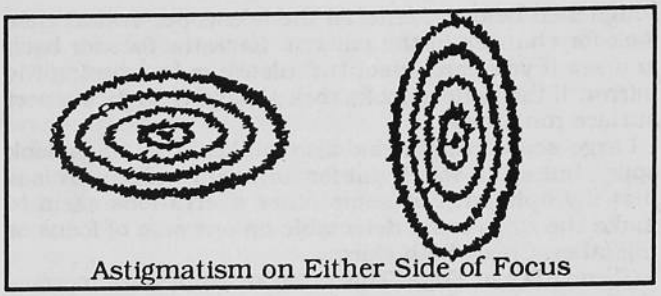
A completely focused image is the most sensitive to error, but it contains no information about where the error occurs, and it is often sensitive to atmospheric problems. The key is finding a happy medium. This generally is where five or six rings are lit up, but you have to see rings before counting is possible. Rings don't often appear in fast mirrors or mirrors for which the surface roughness is high. Also, bad seeing can hide the rings. The safest technique is to rack all the way from too far inside focus to too far outside focus, carefully scrutinizing all the patterns in between.

The star test has been discussed in Taylor's book, in *ATM Book I*, in the April 1983 ASTRONOMY, and in *Build Your Own Telescope*, so I won't go into it in depth here. I'll make do with some figures and some brief explanations.

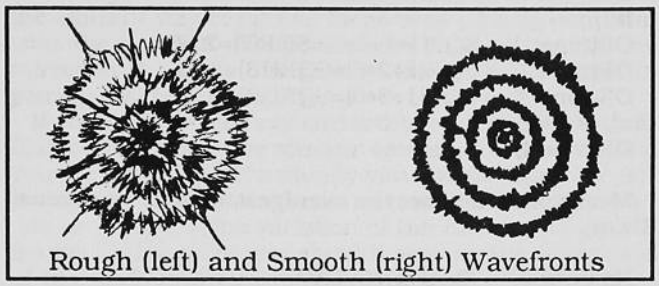
Spherical Aberration. An early description by the Reverend Ellison of this test for mirrors is reprinted in *ATM Book I.* Ellison noted that the correction seemed to change with temperature, and he was critical of this test. Ellison's point was that it was dangerous to figure a mirror using the star test under uncontrolled open air with the plate glasses of his time. With more tempera-



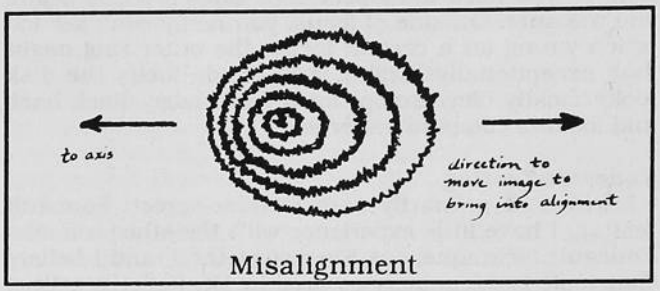
Spherical Aberration on Either Side of Focus



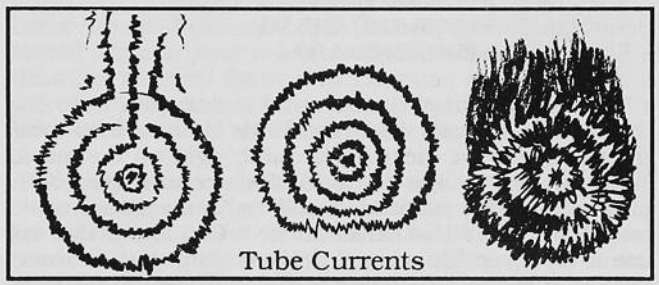
Astigmatism on Either Side of Focus



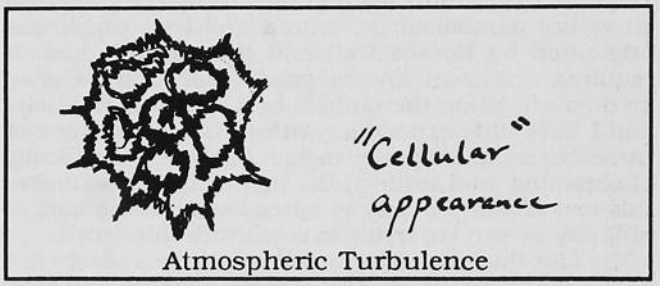
Rough (left) and Smooth (right) Wavefronts



Misalignment



Tube Currents



Atmospheric Turbulence

ture insensitive materials such as Pyrex, the test works fine. At least I have never seen the temperature change rapidly enough to affect my mirror's correction.

You start from focus and roll the focuser first one way and then the other. If you see the same thing on both sides of focus, and the central obstruction appears at about the same distance on both sides of focus, you likely have a good mirror. If there is a significant amount of spherical aberration, you will see a doughnut with a really large hole on one side and a fuzzy-edged image with no central hole on the other. The doughnut appears inside of focus for an undercorrected mirror and beyond focus for an overcorrected mirror. A lot of serviceable fast mirrors fail this test hands-down. You have to be discriminating lest you unfairly judge a mirror too harshly.

Do not be overly concerned if your mirror fails the test for correction. I once star tested a second place optics winner at Stellafane, and IT showed some correction difficulty. But it was also an exceptionally smooth mirror that easily displayed diffraction rings, so that on the whole it was a good mirror.

Misalignment. You really shouldn't star test a misaligned telescope, but you need to recognize misalignment to flag a bad test. Depending on the degree and nature of misalignment, the pattern changes. The pattern depicted in the figure is the tilted, striped cone pattern that appears when misalignment is not too severe. Often a tweak on the main mirror screws is enough to center the image. Stick your hand halfway in front of the telescope (it darkens part of the defocused image) to determine which screw to turn. For complete instructions about this, see a description of this process in Texereau.

Astigmatism. The difference between this pattern and the last is that the image does not appear to be leaning: it appears squashed. The thing about astigmatism is that the direction of elongation moves 90 degrees when passing through focus. Thus astigmatism is most readily detected by rocking the focuser first inside, then outside of focus.

Astigmatism is readily detected in the star test, but it takes a great deal of experience to detect it in the Foucault test. Astigmatism can originate in either mirror. If the secondary bulges out spherically, it is at an angle that produces astigmatism in the images it reflects. If astigmatism is suspected, rotate the main mirror by 45 degrees, realign, and test again. If the astigmatism seemed to rotate 45 degrees too, you've confirmed the main mirror is astigmatic. If it does not, the diagonal is perhaps not flat or you are misinterpreting some astigmatism inherent in your eye. The in-focus astigmatic image is supposed to look like a cross, but my eyesight has never been good enough to more than suspect this effect.

Tube Currents. Persistent tube currents can present almost stationary patterns. On one side of focus the pattern looks stretched in one direction (usually up or down). On the other side of focus it looks flattened. Tube currents are generally influenced by gravity, so stick your hand in front of the optical path and determine if the distorted pattern is oriented up-down.

Roughness. The appearance of rings displaying sharpness and high contrast is an indicator of smoothness of wavefront. The lack of rings is not damning, however, because the wavefront could have been

roughened before it entered the telescope. In that case look for changes in the pattern. Rack the focuser back and see if you can detect turbulence cells crossing the mirror. If the pattern looks rock steady, though, suspect surface roughness.

Large-scale roughness also makes the rings look spiky, but again watch out for turbulence effects. This is just my opinion, but some other aberrations seem to make the rings more detectable on one side of focus or the other. Check both sides.

Turned-Down Edge. This often resembles overcorrection, so you need to inspect both sides of focus before you are sure. Outside of focus, you really can't see too much wrong (at a certain focus, the outer ring might look exceptionally bright), and inside focus the disk looks mostly okay except for a fuzzy edge. Rack back and forth to compare patterns.

Foucault Testing

I will deal primarily with Couder-screen Foucault testing. I have little experience with the other common Foucault technique, the Everest method, and I believe that topic is adequately covered in Mr. Follett's article. There is also a third method that turns the center-of-curvature paraboloid test into a null test, which was originated by Horace Dall and named after him. It requires a lens of known good quality and a good method of setting the pinhole-lens distance precisely, and I have little experience with it. If you have one of these testers, more power to you. I believe the difficulty of obtaining (and testing!) the high-quality lens makes this test of interest only to specialists, not the kind of ordinary person I'm trying to reach with this article.

The first thing I'm going to tell you to do is obtain one of the standard books on telescope making and read the section that explains the Foucault test. These books do a much better job of that than I can because of their superior graphics. I like Texereau's book (*How To Make A Telescope*, Willmann-Bell, 1984), but that is just personal preference.

I hope you will learn from Texereau's treatment that the Foucault test is sensitive to deviations of surface SLOPE rather than surface HEIGHT. All of the mathematical reduction in Texereau is designed to convert surface slope information into height information. This makes certain assumptions about the continuity of the surface and the sampling interval, but all of these assumptions reduce to the following simple principle:

If any zonal irregularities appear that are on the order of one zone wide, do not trust the mirror test reduction procedures.

First you need a mask. I generally fill in the center of my mask, both to acknowledge that the center will be covered by a secondary and to give the mask extra strength. Little information is lost in covering part of the mirror, because the center is difficult to measure anyway. Let's say we wanted to test a 10-inch mirror and put a 2-inch blockage zone in the middle. We note that multiplying by pi to derive the true area is unnecessary, because it's in all of the calculations and would just cancel out. We have an outer radius of 5 inches and an inner radius of 1 inch. (Note: You have to measure your true diameter before you do this.) Let's figure out the area, leaving out pi.

A(5 inches)-A(1 inch)=5•5-1•1=(25-1)=24

So the net "area" we want represented by zones is 24. Let's assume we want a four-zoned mask. We divide the area up into four equal area zones, each with area equal to 6.

Then, to derive all of the zone boundaries starting from the inside, we use the following formula:

The outer radius of Nth zone
=square root (central covered area+N•area per zone)

or,

IR(zone 1) = 1
OR(zone 1) = SQR(1•1+1•6)=SQR(7)=2.66
OR(zone 2) = SQR(1+2•6)=SQR(13)=3.61
OR(zone 3) = SQR(1+3•6)=SQR(19)=4.36
and, of course:
OR(zone 4) = 5

Mean zonal radii are the average values for each zone. Thus:

Rm(zone 1) = (2.66+1)/2=1.83
Rm(zone 2) = (3.61+2.66)/2=3.14
Rm(zone 3) = (4.36+3.61)/2=3.99
Rm(zone 4) = (5+4.35)/2=4.69

Make the height of a zone equal to one quarter to one third of the mirror's diameter. Write these values, plus the values for the mean zonal radii, right on the mask. Texereau shows the Couder mask constructed with parabola values calculated and written on the mask, but I have found that once I make a Couder mask I will use it on several mirrors. I delay adding that information until the test. Besides, I seldom have an accurate value for the radius of curvature when I make the mask.

Zone testing is at best a difficult process. The main difficulty with it is trying to judge the brightness of two separate mask openings. This seems impossible at first, but after you are familiar with the tester and the procedure, your skills will grow until it seems (to onlookers) almost easy, much the same way professional tennis looks easy!

When I set up the test, I do it from a heavy photographic tripod. I know this contradicts nearly any instruction I've ever seen before. Usually they say that unless your apparatus is supported by a single block of granite, your test isn't worth anything. I have found that if you can repeat the zone readings a couple of times, you have made a good test. Find a concrete floor if one is available.

I start up close to the mirror, usually with my Ronchi screen in place and using a very wide or no slit. The Ronchi screen makes an excellent focus "finder" and a lot more light goes through it than through a pinhole or a narrow slit. Consequently, it is harder to lose. (For moving source testers, it is adequate to have the Ronchi screen cover both the tester opening—no slit required—and your viewing area.

For widely separated fixed source testers, narrow the slit to about the spacing of the grating or less and only use the Ronchi screen to cover the viewing area. (Alignment of the grating with respect to the slit again becomes crucial.)

I find the dim reflection of my tester opening in the mirror and I adjust the tripod so I am on axis. I then scoot my chair back about a foot and realign. When I near focus, I try to draw the tripod back slowly, maintaining alignment. When approaching very near focus, I

can discern a limited number of lines through the Ronchi screen. It is here that motion of the tester is most sensitive and you are likely to lose the image. If you do, start over. Eventually this image-finding process becomes second nature.

If you do not possess a Ronchi screen, you can find focus by noting that at focus the imaged slit is the same size as the original, and it is in the same plane as the real slit. (Draw your head back about a foot from the knife and focus your eyes on the real knife and see if the imaged slit is behind it or in front of it.)

When you are within striking distance of the focus, the efficient way of finding focus is by cutting the beam with the knife. If darkness seems to move across the mirror in the same direction as the knife is intruding, you are inside of focus.

If your mirror has any correction on it at all, you will find a place where the shadow seems to be curved. Now you are very close. Eventually you should locate a position where cutting the beam seems nearly instantaneous or you get some variation of the classic "doughnut" figure. At this point you should measure the separation of the knife and mirror. This number is the radius of curvature (or close enough) of the mirror and is equal to twice the focal distance. Use this experimentally determined focus in your calculations for tube drilling rather than the nominal figure. For example, a 6-inch f/8 has a focus distance tolerance that is typically ±1.5 inches. You will also need this number for the reduction procedure.

The next things you look for are qualitative items:

Turned-Down Edge. There are three ways of checking for this. First, insert the knife until the mirror has just become completely dark. There should be a ring on the edge of the mirror of equal brightness on both sides of the mirror. If the side away from the knife is very bright and the side toward the knife is dark, the edge is turned. You can judge the extent of the damage by moving the knife a quarter inch or more inside focus and sweeping the knife to and fro across the beam. Stop when the mirror is one third or two thirds covered by shadow.

Turned edge exhibits a sharply turned shadow near the edge, where it should continue more or less straight to the edge. If you see this, you're looking at a turned-down edge.

The third method is to use a Ronchi screen at the same distance. With the Ronchi screen, don't be fooled by diffraction maxima that form little "echo" images to both sides. (Helpful to this test is a little close-focusing telescope you can assemble from an achromat and a low-power eyepiece. Direct it past the knife or through the Ronchi grating.) At the shadow edge (near the edge of the mirror) you should see the unmistakable evidence of turned edge.

If you are uncertain just how bright a diffraction ring on the edge of the mirror should be, cut out a mask that is smaller than the turned annulus and put it in front of and very near to your mirror while doing the test. Those bright lines at the edge of the mask opening are the lessened aperture's diffraction edges, and unless you have a completely defective mirror, they are perfect diffraction edges with the proper brightness.

Turned far edges (those less than a tenth of an inch wide) I am inclined to let go in unfinished mirrors. Low or run-down outer zones are another matter. The turned far edge is easy to grind off as a last step, but a run-down outer zone must be fixed with a polisher.

Any finished mirror with a turned edge must be judged according to its intended purpose and purchase price. Large mirrors are difficult to make without a turned edge. Masking or painting the edge is the method of choice with these. If, on the other hand, you have paid a premium price for a very high quality planetary telescope, reject the mirror at once.

Rough Surface. To judge this in a finished mirror, try to go to the approximate center of curvature of the innermost zone (see top figure denoting Foucault patterns). The reason for this is that on severely aberrated systems (such as a paraboloid, which is made for looking at infinity, at a distance of only twice the focal length) the Foucault light/dark patterns are so intense the test itself has lost some of its sensitivity to small slopes.

The innermost zone offers the widest expanse of surface area to a sensitive test. You may test for roughness by examining any gray area, but this zone may be very narrow in strongly nonspherical surfaces. Of course, in unfinished mirrors the best time to evaluate your polishing technique for surface smoothness (unsmooth polishing is generally a persistent problem) is when you are nearest the sphere, in which case the gray area is the whole mirror. The Foucault test is at its greatest sensitivity when testing a sphere and is a true null test.

If you see any mottling at all across the gray area, you have a problem with PRIMARY RIPPLE, sometimes called dog-biscuit. But don't judge that this is true until you have looked at it awhile. Slow-moving air currents near the mirror (especially after a polishing session) can mimic surface roughness. Let it sit on the test stand for a while. Look again. If the mottling is sickeningly still, exhibits streaks, or has very slight zones in it, you undoubtedly have a problem with primary ripple.

Ripple is an exasperating problem. It is, I would say, the most common problem in commercial mirrors. But it is not really a primary consideration for low-power deep-sky instruments. More to the point, if you reject a mirror for primary ripple, a second mirror probably won't be any better. My advice is to reject a mirror exhibiting mild primary ripple only if it is to be used for high-power, high-resolution applications and has a high-power price to match.

I recently tested a mirror for a friend. It had an overall average correction good to 1/15 wave but an annoying amount of primary ripple. (I estimated that wavefront roughness exceeded 1/10 wave.) I told him about it, and he elected to keep it. Now he's finished the telescope and is happy with it. There is a lot of fanatic in me concerning this topic. Temper my statements accordingly.

Note: It has become popular lately to blame microripple, or small-scale roughness, for a variety of optical problems. There isn't an easy method of testing conclusively for microripple, unless someone is producing a Lyot phase plate I don't know of. Thus, you must compare these statements to "blaming the dog for bad smells." By its very nature, microripple has an extremely large diffraction structure and hence exhibits itself by a very large, weak halo around bright objects. It can be confused with a dirty mirror and scattering within the eye. But everyone seems willing to attribute every optical defect to microripple, perhaps because it is so mysterious. Microripple is an optical problem, true, but it is primary ripple you must be afraid of, because it puts large amounts of light very near the image. Let's not make microripple a bogeyman.

Overall Correction. The first quantitative test you will do is also the simplest. It would be recognized by Russell Porter. It is to determine the overall correction of

Re-explaining Texereau's TEST DATA SHEET

More people have expressed confusion about the construction of the TEST DATA SHEET in Texereau than about almost any other topic in mirror making. They seem to know instinctively that this is the best path but are put off by the appearance of integrals and too-busy graphs.

This is partially caused by the way Texereau explained the procedure: he explains what goes on each line imbedded in a lot of explanation. It is sometimes difficult to extract just what he meant to be the line's contents from all the explanation. The fancy mathematics were there for explanation -- nothing more — all that's required is arithmetic and patience.

What follows is another explanation of how to make a TEST DATA SHEET. Perhaps you can compare it with the discussion in Texereau, and from the comparison come up with an understanding of the process. There really is no mystery to it.

Precalculate: the radius of the diffraction disk:

rho=1.22•wavelength•(f/D)

with a wavelength of 550E-9 meters or 21.6E-6 inches. These are slightly different values than those Texereau used; they conform more closely to the present standard.

f=R/2=focal length

D=active diameter of mirror

LINE 1: N, the zone-pair numbers on the Couder mask, starting from the inside and working out. These are just labels; they involve no calculation.

LINE 2: hx(N), the OUTER RADIUS of each zone, marked on the Couder mask. [see note 1]

LINE 3: hm(N), the AVERAGE RADIUS of each zone copied from the Couder mask. Take the inside radius (or the outside radius of the next zone in), add it to the outside radius, and divide by two.

LINE 4: hm(N)^2/R, the theoretical parabola you want to follow. Take the average radii, multiply them by themselves, and divide this number by the radius of curvature (the distance between the tester knife and the mirror). [see Note 2]

LINE 5: hm(N)/4f, this is just a useful quantity we will use later. It is the average radii divided by four times the focal length. It equals hm(N)/2R.

LINE 6: D1(N), the actual measurement of the micrometer position of the relative center of curvature. The micrometer scale must increase as you turn the screw to move AWAY from the mirror. During early figuring, when you will have taken only one sequence of measurements, LINE 6 is the same as both LINE 7 and LINE 8. If you have a moving source tester, you must first DOUBLE the measurements before inserting them on LINE 6.

LINE 7: D2(N), same measurement as LINE 6, with the mirror turned 90 degrees to its orientation in LINE 6. If not that, another sequence of test measurements made in the reverse order as those in LINE 6.

LINE 8: D12(N), the average of LINES 6 and 7. It is the sum of LINE 6 and LINE 7 divided by two, or the quantity (D1(N)+D2(N))/2.

LINE 9: D12(N)-constant, the constant is just a micrometer value that is an expression of where you placed the tester on the table. The constant should be approximately equal to:

D12(outer zone)-parabola(outer zone).

The parabola (outer zone) value can be found in the last column in LINE 4, but you will still need to adjust this value some to find the best constant to use. You will do this when you have completed LINE 11.

LINE 10: Residual aberration at center of curvature (COC), this line is equal to LINE 9 minus LINE 4, or :

D12(N)-constant-parabola.

LINE 11: Transverse aberration at FOCUS, LINE 10 times LINE 5. Because these numbers are very small, it is convenient to multiply them by 100,000 and insert that into the table.

Procedure: LINE 11 is only your first cut at the right answer. If the lowest value in LINE 11 is not equal but opposite in sign to the highest value in LINE 11, you must adjust the value of the constant in LINE 9 and then repeat the calculation of LINEs 9, 10, and 11. You can proceed to LINE 12 only after the lowest negative value in LINE 11 is approximately equal to the highest positive value in LINE 11. [see note 3]

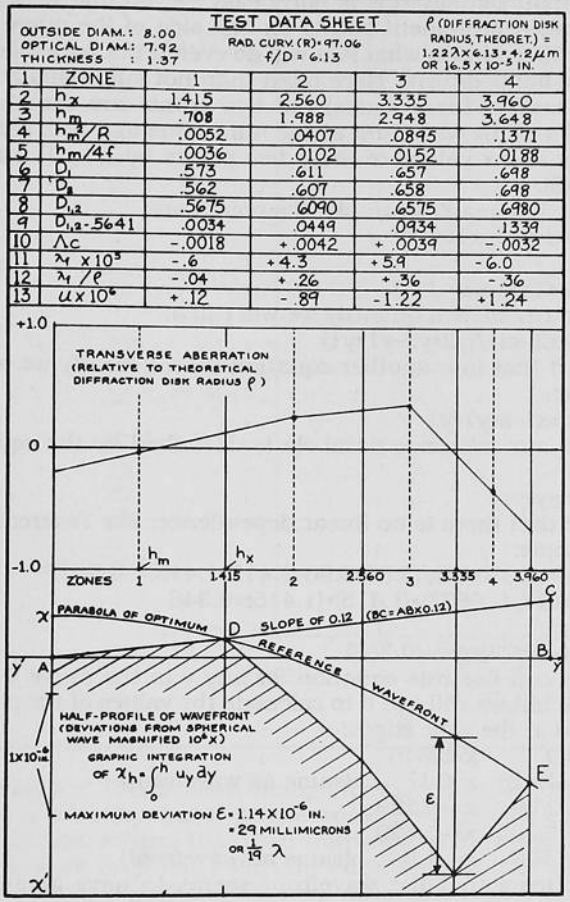
LINE 12: Transverse aberration compared with the Airy disk, LINE 11/rho. Remember, though, that the numbers in LINE 12 are the true values of the transverse aberration, and they have not been multiplied by 100,000 as the numbers in LINE 11 were. The net result is a small number divided by another roughly equal small number. The result should be on the order of one.

Procedure: Plot LINE 12 against the averaged zone radii (LINE 3) on the upper graph on the TEST DATA SHEET. This procedure assumes the curves can be extended with their last known slopes, hence the lines extending all the way to the center and all the way to the edge. If the mirror is sufficiently zoney that this is not a justified assumption, the TEST DATA SHEET will not mean anything.

LINE 13: Error in slope, negative of transverse aberration at focus divided by focal length, or (-LINE 11)/f. Use the true small value of LINE 11. Because you are dividing a very small number, the result is another small number. Again, because it is so small a number, you will multiply it by a million before entering it on LINE 13. Because you will divide the vertical axis of the graph up in units of millionths, you can plot these numbers directly.

Procedure: Graphing the wavefront. Set up the horizontal axis of your graph from a radius of zero to the radius of the mirror (4 inches for an 8-inch mirror, for example). Divide it up into the domains defined by the radii of the edges of the Couder zones (LINE 2) by drawing vertical lines at these points. A vertical axis covering plus and minus ten millionths of an inch will serve for most mirrors. (Note that Texereau ignores the usual mathematical convention and plots his horizontal axis as the "y" axis and his vertical axis the "x" axis.)

To convert the slopes you have calculated into a profile of the mirror, go one unit in the y-axis, and the number of units along the x-axis in LINE 13 (+ is posi-



TEST DATA SHEET

OUTSIDE DIAM.: 8.00
OPTICAL DIAM.: 7.92
THICKNESS : 1.37

RAD. CURV. (R) = 97.06
f/D = 6.13

ρ (DIFFRACTION DISK RADIUS, THEORET.) = 1.22λ x 6.13 = 4.2μm OR 16.5 x 10⁻⁵ IN.

	ZONE	1	2	3	4
2	h_x	1.415	2.560	3.335	3.960
3	h_m	.708	1.988	2.948	3.648
4	h_m^2/R	.0052	.0407	.0895	.1371
5	$h_m/4f$	.0036	.0102	.0152	.0188
6	D_1	.573	.611	.657	.648
7	D_2	.562	.607	.658	.698
8	$D_{1,2}$	.5675	.6090	.6575	.6980
9	$D_{1,2}$-.5641	.0034	.0449	.0934	.1339
10	Δc	-.0018	+.0042	+.0039	-.0032
11	$\lambda_1 \times 10^5$	-.6	+4.3	+5.9	-6.0
12	λ_1/ρ	-.04	+.26	+.36	-.36
13	$u \times 10^6$	+.12	-.89	-1.22	+1.24

Texereau's Test Data Sheet

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How to Make a Telescope, 2nd Edition by Jean Texereau,
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tive, – is negative). Draw a line from your starting point through this point to the line at the domain edge.

In the example in Texereau the slope of the first zone is 0.12. Starting at x=0, go out one unit along the y-axis and then up 0.12 units in the x-axis. Draw a line until it intersects the outside radius of the first zone at 1.415 units. There you stop.

The intersection point becomes the new origin. You next go out one unit (from 1.415 units to 2.415 units), travel down –0.89 units starting from the end of the previous zone's line (that is, from +0.12 units to –0.77 units). Draw a line from your starting point to the line marking the edge of the next domain. The new intersection point becomes another new origin. Repeat until you reach the edge of the mirror. [see note 4]

Procedure: The Reference Parabola: When you have finished, you will have a rough representation of the wavefront, but it may not be focused at the position of minimum wavefront error. To calculate the minimum error, you must fit a parabola to the curve. [see note 5]

This parabola must have two characteristics:

1) It must be an even function (that is, it is "flat" at radius=0 and symmetric about the origin).

2) It must touch the wavefront in two places with the whole wavefront either above or below it. You don't have to calculate an exact curve, a good estimate with these characteristics is enough. Any errors that occur from hand-sketched curves are probably not the largest errors in the test.

Wavefront Error. Take the greatest difference between the reference parabola and the wavefront, divide it by the factor you used to expand the y-axis unit (typically 1 million), and then divide it by the wavelength of light. The result is the wave error. [see note 6]

NOTES

[1] Some people don't have their mask extend completely in to the center, so there is a number (the inside radius of the innermost zone) that is generally marked under a mythical zone label of "0" in LINE 1.

[2] This is really twice the expression for the center of curvature of the zones, but it is the quantity measured by FIXED SOURCE testers. If you have a moving source tester, put this number down anyway, and I will tell you how to adapt your measurements in LINE 6.

[3] OPTIONAL PROCEDURE I: The method I prefer for this iterative process is simpler. Insert into LINE 9 the value of LINE 8 minus LINE 4, or D12(N)–parabola(N). Then in LINE 10 take the constant away. LINE 10 will contain the same number, the residual aberration at the COC, but you are not required to take the parabola away during each calculation.

The iteration is now LINE 10, LINE 11, change constant, LINE 10, LINE 11, change constant,... until the residual aberration at the focus balances as before. I don't know why Texereau chose the order of line operations, because it involves extra work. Perhaps the results in LINE 9 provided him a rough-and-ready comparison to the parabola.

OPTIONAL PROCEDURE II: An even faster method for finding this constant was outlined (with a view toward a graphical analysis) by Adrien Millies-Lacroix. One of the most useful charts was the measurements with the parabola subtracted out. Plot LINE 8 minus LINE 4 (i.e., D12(N)–parabola(N) against zonal radius on a piece of paper [also plot the axes]).

You may find it convenient and more readily graphed if you plot LINE 8 minus LINE 4 on a piece of paper with zero far off the page. Otherwise, including zero might force the M-L tolerance curve to be too squashed to read.

Plot the Millies-Lacroix tolerances (values of plus and minus 2•rho•R/hm(N) on a sheet of acetate at the same scale as your plot above. Connect the points with smooth curves. Move the acetate up and down until the measured points fit neatly within the curves.

The COC constant is the distance you had to lower the measured points to fit them between the tolerance curve. Obtain this from the separation of axes. If we define the distance a point deviates from the axis divided by the amount the tolerance curve deviates from the axis as the "fractional deviation," the closer you can get to the highest fractional deviation equaling the lowest fractional deviation, the better.

Verify the constant by calculating LINE 11 with the

constant you took from the graph. It may take an extra tweak, but you are very close.

As long as you get the transverse aberrations approximately balanced, you can find the wavefront deviation. If you make a slight error in your determination of the LINE 9 constant (or "COC constant"), the resulting reference parabola will be changed a small amount, and the difference will remain about the same -- that's what is so clever about the reference parabola. To derive results, you need not do a precise search for this constant.

[4] In this age of calculators and computers there is really no advantage to finding the points denoting the wavefront by struggling with the graphical method. Use the following algorithm to find each of the points at zone edges:

Nth y-point=hx(N)
zone width=hx(N)-hx(N-1)
Nth x-point=last x-point+slope(N)•zone width

(where • means multiplication)

Using Texereau's example, we find:

The calculations go:

0th x-point is zero, by definition
1st x-point=(0)+(0.12)•(1.415-0)=.170
2nd x-point=.170+(-.89)•(2.56-1.415)=-.85
3rd x-point=-.85+(-1.22)•(3.335-2.56)=-1.80
4th x-point=-1.80+(1.24)•(3.96-3.335)=-1.03

Enter each of the x-points in an extra line, LINE 13b, and plot them versus LINE 2.

[5] To understand why you must fit the wavefront to a reference PARABOLA, you must stare at the diagrams with the capital sigmas on them. Texereau discusses reference spheres compared to the converging wavefront, not parabolas. So, why is he talking about reference parabolas so suddenly?

I once assumed this was an oblique way of saying that the proper form of the mirror is paraboloidal, but he is not saying that here. To explain this, we must note that we are already sitting at the focus of one reference sphere, and we want to know what sitting at the focus of another reference sphere would be like. We are interested only in the DIFFERENCE between these spheres.

The expression for the difference between two spheres can be expanded into a polynomial consisting of terms that mostly cancel, except for a tiny constant (because the spheres are so similar), terms that look like a parabola, and further terms with higher order polynomials that are vanishingly small. So it is tempting to take the largest difference, the parabola offset by the tiny constant, and give it the whole job of representing the difference. That has been done here.

Incidentally, the process of using the reference parabola was shown in Danjon and Couder's *Lunettes et Telescopes*, where it appears in a reduction procedure for the Hartmann test. Texereau appears to have adapted this reduction procedure for the Foucault test to make his TEST DATA SHEET.

OPTIONAL PROCEDURE: Like the wavefront, this parabola is easily calculated. This procedure is not necessary, but for people who understand the following, it may provide an easy way of finding the parabola.

First, decide which two points the parabola must go through. Usually this is fairly easy — you just look for the most prominent points on one side of the curve or the other (this is what you will do even if the parabola is to be hand-drawn). More often than not (and usually in the case of three zones) the two points are the endpoints of the wavefront at the full radius and r=0. Label the y and x values of these two points by (y1,x1) and (y2,x2).

For Texereau's example, the points are:

y1=1.415, x1=0.17

and:

y2=3.96, x2=-1.03.

Then calculate a quantity we will call a:

a=(x2-x1)/(y2•y2-y1•y1)

Insert that into another equation for a quantity we will call c:

c=x1-a•y1•y1

Then our reference parabola is described by the equation:

x=a•y•y+c

Note that there is no linear dependence. For Texereau's example:

a=(-1.03-0.17)/(3.96•3.96-1.415•1.415)=-0.0877
c=0.17-(-.0877)•(1.415)•(1.415)=0.346

so:

x=(-.0877)•y•y+(0.346)

We can use this equation for any y in the range 0 to 3.96, but we will use it to calculate the values of the parabola at the zone edges:

y=0	x=0.346	
y=1.415	x=0.17	(same as wavefront)
y=2.56	x=-0.229	
y=3.335	x=-0.629	
y=3.96	x=-1.03	(same as wavefront)

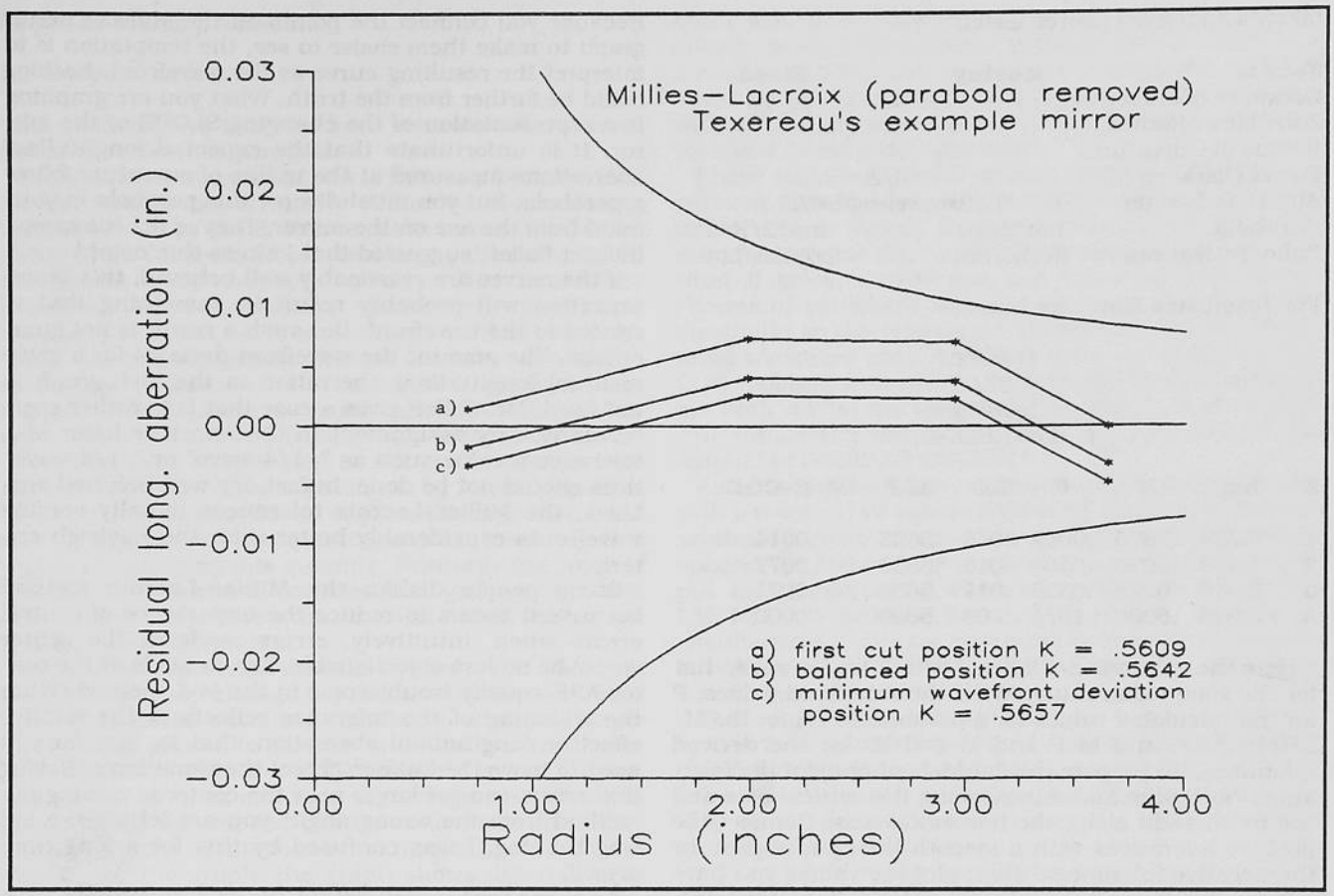
Noticing that the wavefront seems to have greatest deviation from the parabola at y=3.335, we take its value here (-1.8E-6 inches), subtract the parabola value (-0.629E-6 inches), to find a difference of 1.17E-6 inches. We divide that by the length of a wave of green light (21.6E-6 inches) to derive the wavefront deviation of 0.0542 wavelength. Hit the 1/x key on the calculator to invert this to 1/18.4 wavelengths (the slightly different value that Texereau got is a reflection of my slightly different wavelength and details of the round-off errors).

[6] To determine that the reference parabola has been properly chosen:

1) Plot the whole chart mirror-reversed through its center of the mirror. If the reference parabola has a point or dip in the center, you have not drawn the parabola to be symmetric around y=0.

2) Check that the reference parabola touches two widely separated points. For example, if it touches two close-together points (such as the two outermost points) and has a huge deviation at the center, perhaps a parabola cupped the other way would fit better.

3) Check that the reference parabola only "kisses" the two designated points on the wavefront. A reference parabola that intersects the wavefront (that is, crosses to the other side) has the two points chosen incorrectly.



the mirror. This is often enough for slow mirrors. I know this is a heresy, but if people would only get this quantity in line, ensure that their mirrors were zoneless, and make sure they didn't turn the edge, the rest of it would take care of itself and they would produce better mirrors.

I base this conclusion on the many shabby amateur-made mirrors I have tested. It was clear the makers had no idea of how to do even this simple test and relied on the appearance of the shadows. For this I blame the writers in the amateur literature, who emphasized the more elaborate tests in favor of this simple test. They left these poor mirror makers to struggle alone. For the people planning to do more accurate tests, this one is valuable because it tells you if the more complicated test is worthwhile. You should really save the elaborate tests for nearly finished mirrors.

To do this, no mask is necessary. The key is to take micrometer readings at the COC (center of curvature) for the central zone and the COC of the outside zone (see Foucault figure, top and bottom patterns). Once you have done this multiple times and are pretty sure of the results, move the micrometer halfway between these points and check the appearance of the pattern. It should look approximately like the middle pattern.

The overall correction (the distance between COC/outside zone and COC/inner zone) should be approximately equal to or slightly less than r-squared/2R (moving source tester) or r-squared/R (fixed source tester). The COC of the innermost zone should be the CLOSEST to the mirror. If it is not, you don't have positive correction. You have an oblate spheroidal mirror. I have never seen such a case in a finished mirror, but if you are making your own and frequently use the tool-on-top normal stroke, you are often brought naturally to an oblate spheroid.

Advanced Testing Methods

The Millies-Lacroix Method. The problem with previously published descriptions of the "M-L" method is that they don't highlight the really convenient version of this test. It was not mentioned in Robert Miller's article in *TM#6* or in *Build Your Own Telescope* (this treatment contains an unfortunate factor-of-two error that makes the tolerances too wide for a moving source tester). Even in the original *S&T* article in which Millies-Lacroix presented the method, the easy way was shoved to the side. I believe the M-L method has been presented with the parabola included because the parabola is useful to TEACH newcomers about the test, and everyone knows that a paraboloidal figure is what we are trying to approach.

The most convenient version to USE, however, is the one with the theoretical parabola removed from the measured values to produce a flat M-L graph. Such a version is more transparent with regard to which zones have unacceptable slopes. It is very similar to a graph appearing in Texereau showing transverse aberration compared to size of Airy disk, but the graph in Texereau requires considerably more reduction. The flat M-L graph can be done in minutes.

First, you have to make a table like that below, depending on whether you have a moving source tester or a fixed source tester. Some needed quantities appear given in formula form before the table. For example, let's do Texereau's example mirror again, which was

taken with a fixed source tester.

Source	Moving	Fixed
Diameter of Mirror	D	
Zone Mean Radius	hm	
Radius of Curvature	R	
Focus Distance (f)	R/2	
Airy Disk Radius	1.22•wavelength•f/D	
Parabola	hm^2/2R	hm^2/R
Zone Tolerances	R•rho/hm	2•R•rho/hm

For Texereau's Mirror we have:

D=7.92
R=97.06
f=48.53
rho=1.64E-4

Z	hm	M	P	Tol	M-P	M-P-COC
1	0.708	.5675	.0052	.045	.5623	.0014
2	1.988	.6090	.0404	.016	.5686	.0077
3	2.948	.6575	.0895	.011	.5680	.0071
4	3.648	.6980	.1371	.009	.5609	.0000

Here the columns are labeled with Z for the zone, hm for the zone mean raius, M for the measured values, P for the calculated values for a paraboloid, Tol for the M-L tolerance, and M-P and M-P-COC for the derived quantities. To prepare the flat M-L graph, plot the tolerances both plus and minus along the vertical axis and the mean radii along the horizontal axis. Connect the positive tolerances with a smooth line, and repeat for the negative tolerances. Then plot the values you have recorded in the column (MEASUREMENTS-PARABOLA-COC CONSTANT). For the constant I have the value of (MEASUREMENT-PARABOLA) for the outermost zone. Thus, all of the measurements should be on the graph with the outermost zone zeroed.

You can usually get even closer for most mirrors by averaging the values of MEAS-PARA for the outer two zones.

For your next cut at the COC constant, raise or lower the curve in its entirety until the greatest fractional excursion compared with the tolerance is balanced on each side. I have the M-L curve for each case, your first cut, and the balanced values depicted in the figure labeled "Millies-Lacroix (parabola removed)." They appear as curves a and b. Also depicted is curve c, which is the residual longitudinal aberration at the focus position of minimum wavefront error. This is derived from an output from my program MIRROR 1.0, but I will discuss this program in the section on the exploratory focus method.

Once the fractional excursions are significantly inside the tolerance envelope, you have a reasonably good chance of having a diffraction-limited mirror. I say reasonable because there might be a few of you who will apply this test when you should not, i.e., whenever there are sharp zones on the mirror within which you don't really know the shape.

There is also the danger of self-fulfilling prophesies, of "knowing" the answer and making sure you get that answer. The only way of ensuring that you don't do this is to view the mirror as an adversary. "Mirrors are guilty until proven innocent" is a good adage to follow. Force your mirror to prove it is worth keeping. Don't be the mirror's apologist.

One warning for potential users of this method: Because you connect the points on the Millies-Lacroix graph to make them easier to see, the temptation is to interpret the resulting curve as the wavefront. Nothing could be farther from the truth. What you are graphing is a representation of the changing SLOPE of the mirror. It is unfortunate that the expected longitudinal aberrations measured at the radius of curvature follow a parabola, but you must divorce this parabola in your mind from the one on the mirror. They're not the same. (Robert Follett suggested that I stress this point.)

If the curves are reasonably well behaved, this representation will probably result in something that is related to the wavefront, but such a result is not guaranteed. The amount the wavefront deviates for a given residual longitudinal aberration in the M-L graph is not fixed. Mr. Follett gives a case that fails rather spectacularly. Any assignment to the upper or lower M-L tolerance a value such as "+1/4 wave" or "-1/4 wave" thus should not be done. In fact, for well-behaved surfaces, the Millies-Lacroix tolerances usually confine wavefronts considerably better than the Rayleigh criterion.

Some people dislike the Millies-Lacroix method because it seems to reduce the importance of central errors when, intuitively, errors made at the center would be no less objectionable. Errors made at the center ARE equally troublesome in the M-L method. What the widening of the tolerance reflects is the relative effect on longitudinal aberration, that is, how far you need to move the knife to detect the same error. Saying that errors can get larger near the center is viewing the method from the wrong angle: you are letting the tail wag the dog. I was confused by this for a long time myself.

A mirror that is well within the M-L tolerances, is a surface of revolution, has a smooth figure and a good edge is finished as well as the Foucault test can do it. You need to perform the rest of the calculation described in Texereau only if you want a wave-error value to brag about. Such a number will probably be science fiction though. There are enough inaccuracies and uncertainties in this entire process that claims of wavefront accuracy exceeding 1/10-wave are probably moonshine.

The Method of Exploratory Focus

I have developed a method that is a slight variation on the method appearing in Texereau, much in the same sense as the Millies-Lacroix technique is a variation of Texereau's procedure. The method was an outgrowth of a computer program I wrote to do both the M-L procedure and the Texereau wavefront error calculation, spurred on by the cumbersome numerical procedure of choosing the reference parabola properly.

You wouldn't believe how a procedure that's so easy to do by hand can be made difficult when telling a computer to do it. A measure of the difficulty of this procedure is demonstrated by the program supplied by the publisher in the appendix of Texereau. This procedure only works some of the time; part of the reason for this failure is that it's so difficult to tell the computer how to choose this parabola in every situation.

Because of this difficulty, I took the easy way out and wrote a procedure that did the COC constant search (the search for the constant in Texereau's Line 9) not using the transverse aberration as my measure of goodness of fit but on the total wavefront deviation itself. In other words, I pick the COC constant such that the reference parabola is a straight, flat line, which cor-

responds to this parabola:

$x=a \cdot y \cdot y+c$ with $a=0$.

This method gives the wavefront error directly without use of the reference parabola.

I suspect Texereau didn't do it this way because this method would be extremely difficult—and certainly tedious—to do by hand. You've got to remember that in 1951, when Texereau's book was first published, digital computers were in their infancy. This procedure requires you to complete the entire calculation sequence between each trial change of this constant. Truly this is a staggering amount of work, even with a calculator. Nowadays, when computers are commodities sold next to the auto parts section of K-mart, this calculation and related calculations become easy.

It was only a simple step to the realization that we can change the focus position by changing this "constant." It is possible to explore the region of focus and calculate various quantities of interest in this region by changing this quantity. Naturally the value of the COC constant still contains the "garbage" position of the micrometer screw, but the RELATIVE values can give us much information.

I was also concerned that the procedure in Texereau would drastically change the focus until the wavefront referred to in the wavefront calculation would no longer be remotely related to the one in the tranverse aberration graph. To obtain a self-consistent set of graphs, you should go back and redo the transverse aberration graph using the implied change of focus in the reference parabola. This focus change cannot be read directly off the graph: the graph shows differences in the sagitta of the reference spheres, and you must figure out how that affects changes in the COC constant. I suspected it wouldn't make much difference except for distorted wavefronts, and that is how it turned out. I imagine the reason that Texereau didn't emphasize this point is that for high-quality mirrors such as the one appearing in his example it does not make a significant difference.

The basic change in orientation used in this method is that you need to regard the COC constant not as a single quantity you need to find to remove from the calculation but as a VARIABLE. You will slide this quantity through the range of proper focus—because that is what changes of this number represent—recalculating the values of the interesting quantities as you go.

The other change in orientation required is that it is no longer necessary to use the reference parabola. This parabola was a clever stratagem to move focus slightly from the position of minimum transverse aberration to the position of minimum wavefront error. Because we now regard focus as a variable, it is no longer necessary or proper to do this. We will find BOTH positions. The wavefront error in these calculations will be simply the difference between the maximum in the wavefront graph and the minimum in that graph.

Perhaps a mention of how changes in this constant (it is a "constant" subtracted from each zone reading within a single calculation) is related to real changes in the focus position will help alleviate confusion. When you do this test, you do it at the center of curvature (the COC), and the math of the reduction procedure in Texereau is oriented toward a fixed-source tester. You need to divide by a factor of 2 to find the true changes in the zonal COC and another factor of 2 to move it to the focus. Therefore, motions in the fixed-tester COC constant will be 4 times motion at the infinity focus. A change in the COC constant of 0.020 inches represents a change of 0.005 inches at focus when directed at the stars. Early on I compared the results of this procedure with an analytic expression for "depth of focus" in Sidgwick and found good agreement.

I have supplied a small generic routine—GENMIR—to perform the calculations needed in this procedure in millimeters or inches. It makes an automatic choice of range and value for the COC constant. After you see what it gives, maybe you can come up with better choices of increment size and limits. It calculates the maximum in the transverse aberration and the maximum wavefront error and puts them out alongside the COC constant with which it calculated them. When they are both within the tolerance (presently set at ±1 Airy disk radius and within 1/4 wave), it prints next to the output "<< OVERLAP REGION."

As an example of this program's output I show a run with a 6-inch f/10 sphere with every zone measurement arbitrarily given as equal to 1, that is, for a perfect sphere. We learn a few surprising facts from this output, most important of which is that there is NO OVERLAP REGION with the 6-inch f/10 sphere. There is no simultaneous focus for which the transverse aberration is both smaller than the Airy disk and the wavefront has deviation less than 1/4 wave.

This might seem strange to those familiar with the results for a sphere that say a 6-inch is within 1/4 wave at f/8.2 and within the Millies-Lacroix tolerances at f/9.5 (or thereabouts). Both these conditions are met, but they are not met at the same focus. Not until f/10.25 do these focus regions overlap.

People might recognize these criteria as the Danjon and Couder (D&C) conditions. These conditions appear in Texereau as:

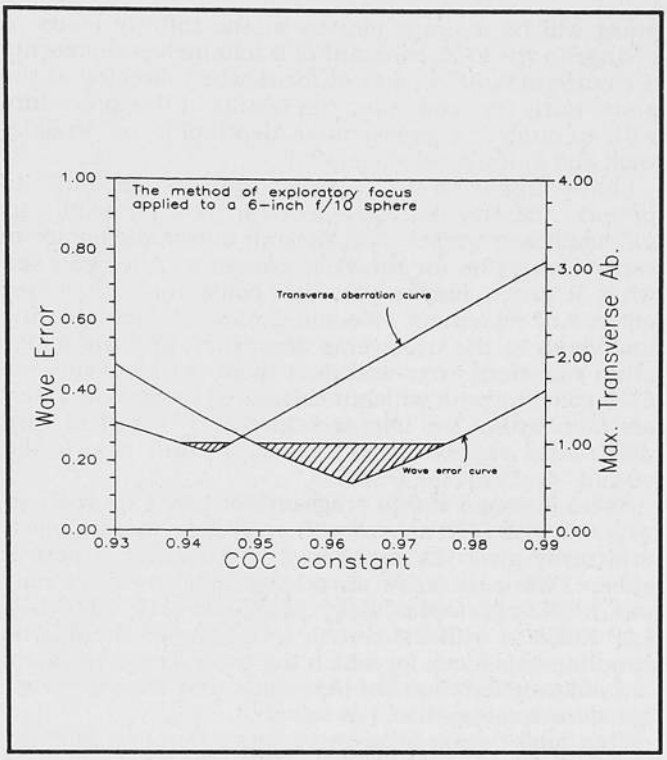
D&C #1) The radius of the circle of least aberration should be comparable with that of the theoretical diffraction disk and, on the average, the transverse aberrations should not exceed the diffraction disk radius.

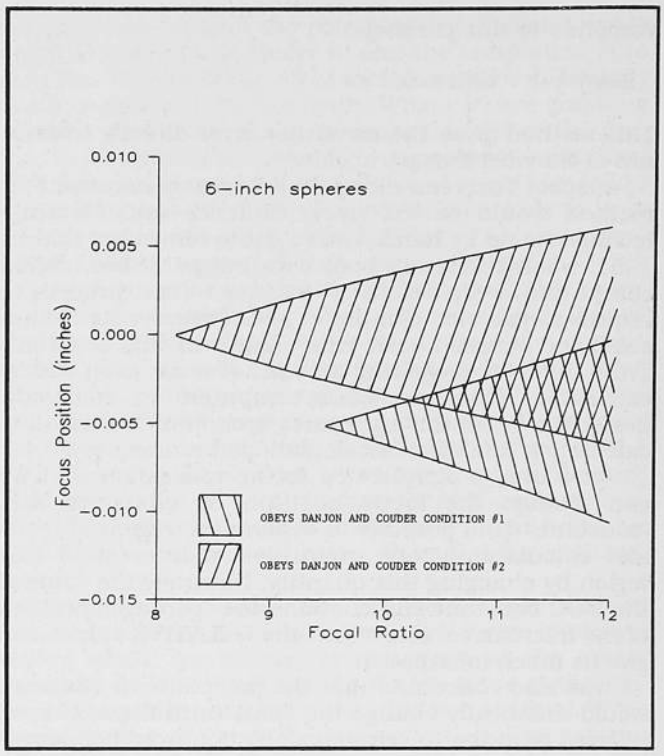
D&C #2) Maximum wavefront error must not exceed a quarter wave and, for the major part of the mirror surface, the defects should be appreciably less.

Although the conditions appear here as guidelines, it is more usual to interpret them in their strictest sense. For example, in condition #1 you are allowed to sneak outside the diffraction disk radius as long as you do not exceed it for a large fraction of the area. In the M-L method, however, you are forbidden to have any portion of the mirror deflect rays outside the diffraction disk. There are two reasons for this. First, you are sampling the surface. You don't know what it's doing everywhere, so it is safer if you keep well inside the limits on the parts you do know about. Second, the diffraction "disk" isn't really a disk. It's a function with most of the light concentrated at the center. The theoretical diffraction disk is unlit at the edge.

It is important to recognize that the term "diffraction-limited" refers to D&C condition #1, not D&C condition #2. A lot of manufacturers either don't know this fact, or they tend to ignore it. A mirror can be well-within 1/4 wave on the wavefront but a long way from diffraction-limited. This term really applies to "sensibly perfect" optics, and 1/4 wave is still "noticeably imperfect."

The behavior of a 6-inch f/10 sphere as generated using GENMIR at small stepsize is given in the plot





titled, "The method of exploratory focus ..." There I plot the maximum transverse aberration of this sphere along with the wave error curve versus the COC constant. The hatched regions are the amount by which the curves exceed the appropriate D&C condition. Note that for a 6-inch f/10 sphere these regions do not intersect.

By picking off the edges of the hatched regions, I have plotted the behavior of 6-inch spheres of various focal ratios in the figure labeled "Six-inch spheres." You can see that D&C condition #2 opens up at about f/8.2, while while condition #1 is satisfied at about f/9.5, but they do not overlap until f/10.25. Given that you'd like to do a bit better than the absolute minimum requirement, 6-inch spheres do not approach perfection until about f/11 and above.

This matches observation. I had a chance to look through a sphere with focal ratio a little over f/8 and found the image horrible. A planet was a fuzzball with no details visible. At f/10 the image had improved greatly, but aberrations were still visible. A very nice f/12 sphere gave excellent images.

I calculated the incoherently illuminated optical transfer function (OTF) of an f/8.3 mirror for the viewing conditions. This plot is dominated by spherical aberration. I moved focus only far enough to go to the position where I was likely to have focused the instrument. You can see the contrast is near that of a perfect aperture at only very low and very high spatial frequencies with a considerable sag at middle frequencies. The 1/20th-wave defocus refers again to changes in the sagitta, not how far you change the focuser. By the way, this graph is a "prettied" output of the OTF procedure of my program APODIZE (see "Changing the Aperture Pupil," *TM#29*).

These plots are meant more as demonstrations of the behavior of mirrors than as illustrations of the method. The method actually requires a much simpler plot. This is illustrated in the figure titled "Texereau's Mirror in the Method of Exploratory Focus." We plot COC constant or focus (divide by four) along the vertical axis. We pick off each end of the appropriate zone where each of the D&C conditions holds and plot it at the COC constant where it was true. We do the same for a perfect mirror (simply put the theoretical parabola values into the program). Nothing is plotted along the horizontal axis: we just offset the D&C conditions for the real and perfect mirrors.

Because the relative values of the COC constant differ in the real and perfect mirrors (it should be around zero for the perfect mirror but contain the arbitrary micrometer reading for the real mirror), make an arbitrary zero point at the point of best wavefront error for each and plot them side by side. You are only interested in the relative value of the COC constant, not its absolute magnitude.

What does this diagram tell us? The first thing it says is that Texereau has just about made a perfect mirror. Note the similarity in relative position and size between the real and perfect mirrors. If you were to do this for the 6-inch f/10 mirror, you would see greatly reduced regions of applicability of the D&C conditions as well as the lack of overlap.

Condition #1 of Danjon and Couder seems to suffer from aberration much more quickly than condition #2. This is what I believe Texereau meant when he said "For small mirrors, generally speaking, the first condition is the more difficult to satisfy." A person looking at the regions in which both D&C conditions are obeyed for the perfect mirror might conclude that condition #1 is bigger and hence easier to hit. In the presence of aberration, though, it gets smaller much faster.

By the way, the region of focus that D&C#1 applies is 1.22 times as large as the region that D&C#2 applies in perfect mirrors. In real mirrors it is rare to see this region larger than that of the 1/4-wave region.

If the real mirror is bad, two things are evident: 1) one or both of the regions of applicability are significantly

Listing of GENMIR.BAS

```
100 REM Generic Mirror Reduction Program by Dick Suiter
110 REM    This program is written for an 80 column screen.
120 REM It may need modification to give "pretty" output
130 REM for a 40 column screen.  I also advise changing the
140 REM output to the printer, if any (PRINT to LPRINT).
150 REM R1(I) is Couder screen information
160 REM R2(I) are the mean zone radii
170 REM M(I) are averaged zone measurements
180 REM L(I) are residual COC aberrations
190 REM T(I) contains aberrations at focus in units of P
200 REM S(I) contains slopes * 1E6
210 REM W(I) contains wavefront * 1E6, W1 min, W2 max
220 REM R is radius of curvature, A(I) contains parabola
230 REM P is radius if diffraction disk, T1 is max T error
240 REM F is focal length, E is max total wavefront error
250 DIM R1(10), R2(9), M(9), L(9), T(9), S(9), A(9), W(10)
260 INPUT "MILLIMETER UNITS (1) OR INCHES UNITS (0)? ",Q1
270 U = 21.6
280 IF Q1 = 1 THEN U = 550
290 INPUT "ACTIVE DIAMETER OF MIRROR ",D
300 INPUT "RADIUS OF CURVATURE ",R
310 F = R/2
320 P = 1.22*U*.000001*F/D
330 INPUT "NUMBER OF ZONES? (UP TO 9) ",N
340 INPUT " INSIDE RADIUS OF ZONE 1 ? ",R1(1)
350 FOR I = 2 TO N+1
360 PRINT "OUTSIDE RADIUS OF ZONE";I-1;
370 INPUT R1(I)
380 R2(I-1)=(R1(I)+R1(I-1))/2
390 A(I-1)=R2(I-1)^2/R
400 NEXT I
410 PRINT
420 PRINT "MEAN R","  PARABOLA","M-L TOLERANCE"
430 FOR I = 1 TO N
440 PRINT R2(I), A(I), 2*P*R/R2(I)
450 NEXT I
460 PRINT
470 PRINT "PUT IN AVERAGED ZONE MEASUREMENTS "
480 FOR I = 1 TO N
490 PRINT "Measurement for zone #";I;
500 INPUT M(I)
510 NEXT I
520 PRINT
530 C = (M(N)-A(N)+M(N-1)-A(N-1))/2
540 PRINT "COC constant somewhere around ";C
550 V = 2*P*R/R2(N)
560 PRINT "Size of strongly varying region about +/-";V
570 INPUT "FIRST VALUE OF COC CONSTANT? (999 defaults) ",C1
580 IF C1 <> 999 THEN 630
590 C1 =  C - 2*V
600 C2 =  C + 2*V
610 C3 =  V/5
620 GOTO 650
630 INPUT "LAST VALUE OF COC CONSTANT? ",C2
640 INPUT "STEPSIZE OF COC CONSTANT? ",C3
650 PRINT "Mirror D:";D;"  Radius of Curvature:";R
660 PRINT
670 PRINT "COC CONSTANT";" WAVE ERROR 1/ ";" T.Ab. IN P "
680 REM Update calculations ******************************
690 FOR X = C1 TO C2 STEP C3
700 FOR I1 = 1 TO N
710 L(I1) =  M(I1)-A(I1)-X
720 NEXT I1
730 GOSUB 760
740 NEXT X
750 GOTO 570
760 REM  W(1) = 0  by definition
770 T1 = 0
780 FOR I = 1 TO N
790 T(I) = L(I)*R2(I)/(2*R*P)
800 IF ABS(T(I)) > T1 THEN T1= ABS(T(I))
810 S(I) = -T(I)*P*1000000!/F
820 W(I+1) = (R1(I+1)-R1(I))*S(I) + W(I)
830 NEXT I
840 REM This extends aberration linearly to edge **************
850 T2 = T(N-1)+(R1(N+1)-R2(N-1))*(T(N)-T(N-1))/(R2(N)-R2(N-1))
860 IF ABS(T2) > T1 THEN T1=ABS(T2)
870 REM ***************************************************
880 GOSUB 920
890 GOSUB 1020
900 RETURN
910 REM ************************************************
920 REM   Wave error subroutine
930 W1 = 1E+10
940 W2 = -1E+10
950 FOR J = 1 TO N+1
960 IF W(J)> W2 THEN W2 = W(J)
970 IF W(J)< W1 THEN W1 = W(J)
980 NEXT J
990 E = 1/((W2-W1)/U)
1000 RETURN
1010 REM ************************************************
1020 REM  Printing results
1025 REM  TAB only for prettiness, remove if won't run
1030 PRINT X, E, T1, TAB(45);
1032 IF E  < 4 THEN PRINT "  ";
1034 IF E  > 4 THEN PRINT " <";
1036 IF T1 < 1 THEN PRINT ">";
1040 IF E > 4 AND T1 < 1 THEN PRINT " << OVERLAP REGION";
1050 PRINT
1060 RETURN
```

smaller than the equivalent regions for a perfect mirror, and 2) the regions of applicability don't line up or overlap only slightly. In this case it is incorrect to take the wave error as the minimum value. The wave error in the region of overlap gives a much more realistic appraisal of the performance of the mirror.

We can use these characteristics to formulate an addendum to the conditions of Danjon and Couder:

Addendum to D&C: For excellent mirrors, the focal regions of applicability of D&C conditions #1 and #2 should overlap strongly and should be approximately the same size as those regions for a perfect mirror.

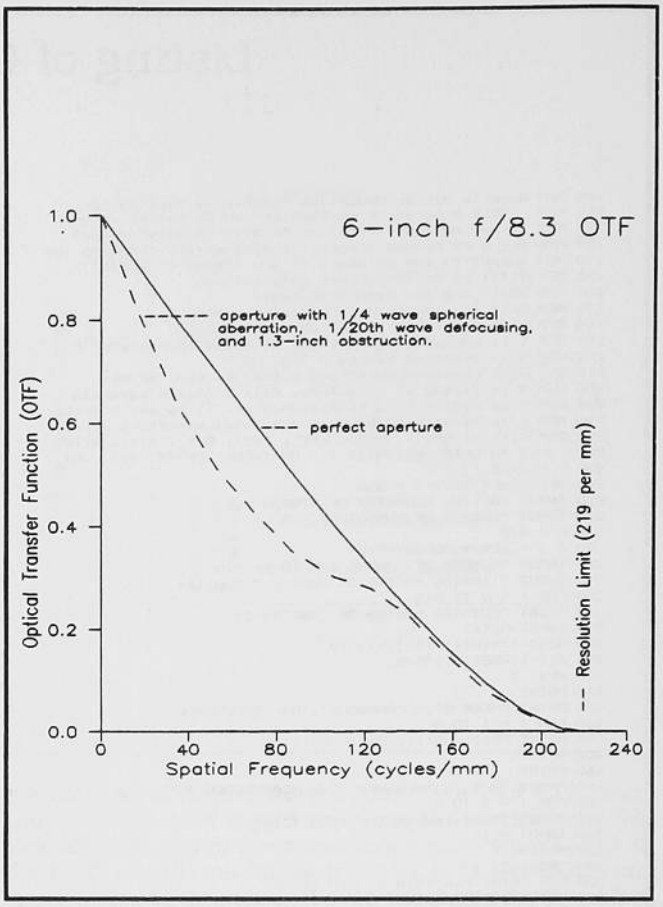
The original appearance of the conditions of Danjon and Couder in their book *Lunettes et Telescopes* (1935) is a bit stronger than the version eventually passing through Texereau and the translator Strickler. Please forgive my translation, but the sentence preceding the appearance of the conditions says, loosely: "An objective will not be judged good until it SIMULTANEOUSLY satisfies these two conditions:..." [emphasis mine]. Thus, Danjon and Couder were aware of this focus shift problem fifty years ago.

I should mention that calculations of transverse aberration should not be taken too seriously when they get smaller than the Airy disk. Light is a wave and will not go exactly where these geometrical calculations say it will. The Foucault test as presented for amateur workers has a ray-optics viewpoint instead of the more correct viewpoint of wave optics. What we are more worried about and what we are specifying in this addendum is that we have a smooth, well-corrected surface.

For mirror analysis, I have another program besides GENMIR. Called MIRROR 1.0, the program does the complete calculation appearing here, including graphs and a detailed report, for any given COC constant, or if you prefer, it will search for the position of the minimum wavefront. MIRROR 1.0 is written for IBM-PCs and compatibles. Presently it only does calculations in inches. I am distributing it as shareware, and you can obtain it either from *Telescope Making* or directly from me.

Output from GENMIR

```
MILLIMETER UNITS (1) OR INCHES UNITS (0)?  0
ACTIVE DIAMETER OF MIRROR  6
RADIUS OF CURVATURE  120
NUMBER OF ZONES? (UP TO 9)  7

 INSIDE RADIUS OF FIRST ZONE?  0
OUTSIDE RADIUS OF ZONE 1  .5
OUTSIDE RADIUS OF ZONE 2  1
OUTSIDE RADIUS OF ZONE 3  1.5
OUTSIDE RADIUS OF ZONE 4  2
OUTSIDE RADIUS OF ZONE 5  2.5
OUTSIDE RADIUS OF ZONE 6  3
OUTSIDE RADIUS OF ZONE 7  3

MEAN R          PARABOLA      M-L TOLERANCE
 .25            5.208334E-04   .2529792
 .75            .0046875       8.432641E-02
 1.25           1.302083E-02   5.059584E-02
 1.75           2.552083E-02   3.613989E-02
 2.25           .0421875       .0281088
 2.75           6.302083E-02   2.299811E-02
 3              .075           .0210816

PUT IN AVERAGED ZONE MEASUREMENTS
Measurement for zone # 1  1
Measurement for zone # 2  1
Measurement for zone # 3  1
Measurement for zone # 4  1
Measurement for zone # 5  1
Measurement for zone # 6  1
Measurement for zone # 7  1

COC constant somewhere around  .9309896
Size of strongly varying region about +/-  .0210816
FIRST VALUE OF COC CONSTANT? (999 defaults)  999

Mirror D: 6   Radius of Curvature: 120

COC CONSTANT  WAVE ERROR 1/  T.Ab. IN P
 .8888264      .9316067      2.454251
 .8930427      .9877378      2.304251
 .8972591      1.051067      2.154252
 .9014754      1.123072      2.080033
 .9056917      1.205669      1.903367
 .909908       1.30138       1.7867
 .9141243      1.413598      1.670034
 .9183406      1.546994      1.553367
 .9225569      1.708189      1.436701
 .9267733      1.906886      1.320034
 .9309896      2.157892      1.203368
 .9352059      2.484994      1.086701
 .9394222      2.839173      .9700348
 .9436385      3.227324      .8841118
 .9478548      3.738413      1.084111
 .9520711      4.441836      1.284111
 .9562874      5.471325      1.484111
 .9605038      6.66027       1.68411
 .9647201      6.774892      1.88411
 .9689364      5.509468      2.08411
 .9731527      4.642643      2.284109
FIRST VALUE OF COC CONSTANT? (999 defaults)  .93
LAST VALUE OF COC CONSTANT?  .98
STEPSIZE OF COC CONSTANT?  .002

Mirror D: 6   Radius of Curvature: 120

COC CONSTANT  WAVE ERROR 1/  T.Ab. IN P
 .93            2.093225      1.230749
 .932           2.228179      1.175409
 .934           2.381733      1.120069
 .9359999       2.55802       1.06473
 .9379999       2.728477      1.00939
 .9399999       2.886742      .95405
 .9419999       3.064499      .8987102
 .9439998       3.265383      .901251
 .9459998       3.49491       .9961193
 .9479998       3.758879      1.090987
 .9499998       4.06598       1.185856
 .9519997       4.427727      1.280724
 .9539997       4.860128      1.375592
 .9559997       5.386123      1.47046
 .9579997       6.015196      1.565329
 .9599996       6.519513      1.660197
 .9619996       7.116133      1.755065
 .9639996       7.050901      1.849933
 .9659995       6.333093      1.944802
 .9679995       5.747932      2.03967
 .9699995       5.261758      2.134538
 .9719995       4.851415      2.229406
 .9739994       4.500444      2.324275
 .9759994       4.122828      2.419143
 .9779994       3.784251      2.514011
 .9799994       3.497064      2.608879
```



Systematic Error in Couder-Screen Testing?

I have tested a lot of mirrors, and I believe I have detected a systematic error in my testing. I do not understand the reason for this error. It could be a biased interpretation of the shadows within me. It could reside in my testers or in the eyepieces I star test with. It might be a fundamental error in Couder-screen testing itself. I'll leave that up to others and just tell you about it.

The Couder-screen Foucault test, as I apply it, seems to overestimate correction at fast focal ratios. When the correction seems perfect at the bench, I take the mirror outside and inevitably find the mirror undercorrected. This does not happen with slow mirrors (the transition point is about f/6).

Because of this, I view the star-test component of testing as crucial to making fast mirrors. It's a luxury to star test f/8 mirrors but not absolutely necessary. For an f/5 mirror, it's not optional.

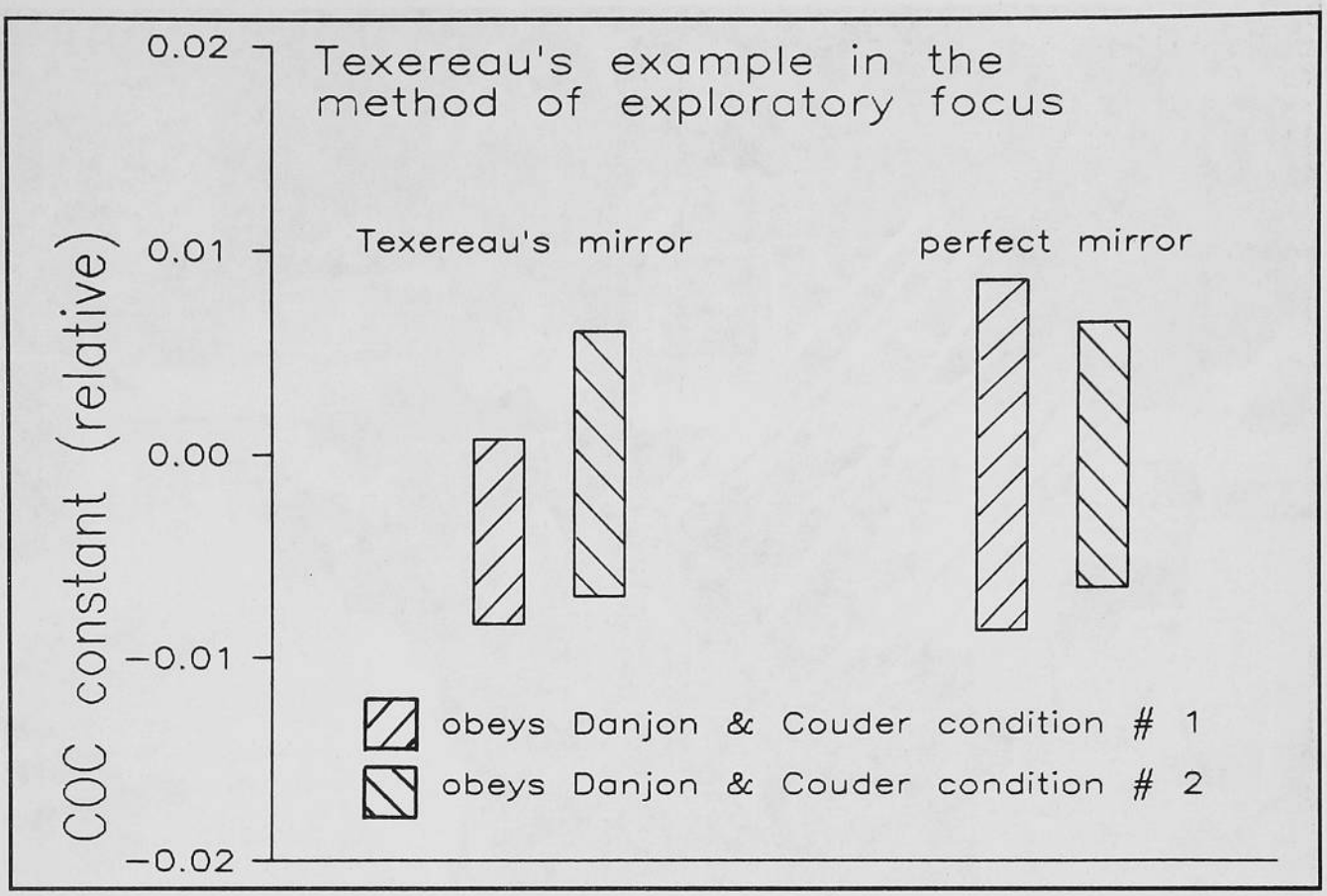
Bench versus Point Source Testing

Some people may believe I am partial to the star (or "point source") test and prefer it to bench testing. I do not. However, I recognize that the star test can perhaps be done by less experienced people with a lower probability of error than the Foucault test. If you are like me, losing much of your skill in Foucault testing in the long periods between mirrors, the star test can provide a useful benchmark. But it is my belief that both Foucault testing and point source testing can be used to good effect to make better mirrors.

Suiter's Mirror-Test Cookbook

I will conclude with a quick cookbook approach to my method of testing.

1) Calculate and make a Couder screen.
2) Measure the mirror's radius of curvature.
3) On a screenless mirror, check the edge.
4) Check the surface for a smooth appearance.
5) Check that there are no sharp zones.
6) Check that the total correction is in the ballpark and that the crest of the doughnut is about on the 70 percent zone at the halfway point of the correction.
STOP HERE IF ANY OF THE ABOVE IS BAD
7) Put the screen on the mirror.
8) Make the zonal measurements. Get a consistent set, moving through the zones both forward and backward.
9) Turn the mirror 90 degrees. Do the zonal measurements again. Average all the measurements for each zone.
10) Make a parabola-removed Millies-Lacroix chart. Be suspicious of any zone protruding out of the toler-



ance envelope.
11) If your measurements have been taken with a moving source tester, double them.
12) Run GENMIR or MIRROR both for real measurements and perfect mirror.
13) Do plot of edges of focal regions where wavefront is better than 1/4 wave and light is diverted to less than Airy disk radius. Do this for real and perfect mirror using the same D and R.
14) If mirror passes Foucault test, take it outside and star test it. Look especially for astigmatism, because that is one flaw for which the Foucault test is not optimized and for which Foucault test users must be very skilled.

Wrap-Up

In these days of fairly low mirror prices and unbelievably high mirror-making prices, the old justification of lower cost doesn't work any more. The only reason to make mirrors is the quest for high quality, and that equals good testing. Good testing requires comprehension of the process of testing.

People have traditionally gone for the fast or easy solution—do what Howard, or Thompson, or Texereau, or even Sam Brown said—without understanding the why or wherefore. That attitude was fine back in the old days when telescope makers were people who happened to want telescopes. But present day telescope makers make telescopes, supposedly, because they like to do it.

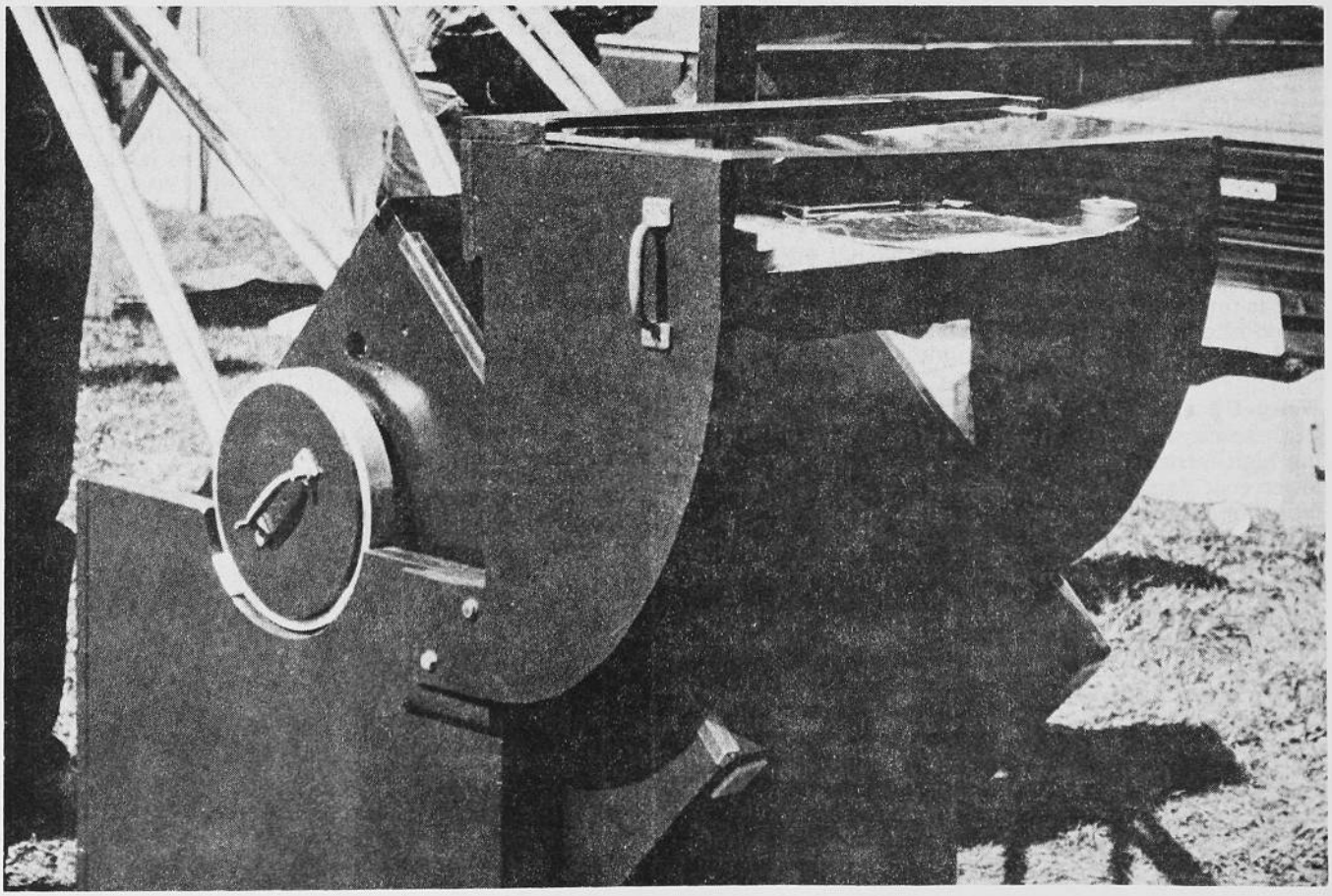
That requires some sort of justification, and one such justification is better quality. There is a common myth among telescope makers that says, boiled down: "Handmade mirrors are better than commercial mirrors because they've been loved." That just isn't true. In the introduction I described commercial makers as somewhat unscrupulous, and some of them are, but most are competent. Commercial mirrors might be best described as the fast food chains of mirror making. You seldom get a mirror (or a meal) that is very good, but you seldom get one that is very bad either. To be able to beat that minimum quality in making your own mirrors, you must understand the process of testing. The old voodoo approach must be replaced by one of comprehension.

My advice to beginning mirror makers is to go ahead and make a few mirrors by rote but to accept the fact that someday you will have to approach the art at a higher level.

My advice to nonmirror makers is to continue to use the testing methods, by rote or otherwise, to find and reject seriously defective commercial mirrors that inevitably slip out of the optical shops. Maybe if enough of us do this, the general quality of commercial mirrors will improve, but I doubt it. Manufacturers have always found money is better spent in advertising than in making better products.

Whether you learn something from my method of exploratory focus or from Robert Follett's K1•K2 method (to be published in an upcoming issue of *TM*) or even use the tried-and-true techniques of Texereau, at least you will be helped toward better mirrors.

Dick Suiter
425 East 19th Street #106
Panama City, FL 32405



Astrofest 1987

A big turnout and lots of fine telescopes made last year's Astrofest the best ever.

I've attended every meeting of Astrofest since it moved to Kankakee, Illinois—and this 1987 gathering of midwestern telescope makers and amateur astronomers was the best ever. At the end of the meeting in the lecture hall it was announced that all records had been broken: twenty-two societies were present, people from twelve states, and a record attendance of 382 persons.

More vendors were present than ever before too, which enabled those attending a bit of hands-on familiarity with products they wished to buy. At the swap meet, many amateurs showed off items they wished to get out of the basement or attic, but in most cases I suspect most of them bought more than they sold and went home carrying more than they started with.

I rolled in from O'Fallon at about 3:30 p.m. Friday, a drive of about 285 miles. The prospects didn't look encouraging then, with dark, somewhat cloudy skies and just a few instruments displayed on the telescope field. I decided to examine the displays and make a photo record the following day.

Between examining the many instruments on the telescope field and trying to assist delegates who came up with questions about telescopes and optics, I usually find it impossible to attend the many fine papers that are presented. I'll tell you about what I saw with due apologies to the people who presented papers.

The massive 17.5-inch Dobsonian by Bill Burton of Columbus, Ohio. caught my eye first. With a pocket computer program and surveyor's inclinometer and compass, Burton can find objects anywhere in the sky. The azimuth is read off the compass—which is illuminated by a red LED and viewed through a magnifying port. The telescope can be set quite accurately, easily putting an object in the field of a low-power ocular. The inclinometer sets the altitude. A shelf on the rear of the Dobsonian mount with a clear plastic cover against dew allows one to see star charts and operate the computer at all times. The illumination is Hewlett Packard 120 candlelaria LEDs, the brightest commercially available. Once the mount is leveled using the azimuth and altitude readouts and the computer program he wrote with its stored objects, sky hopping becomes quick and exciting.

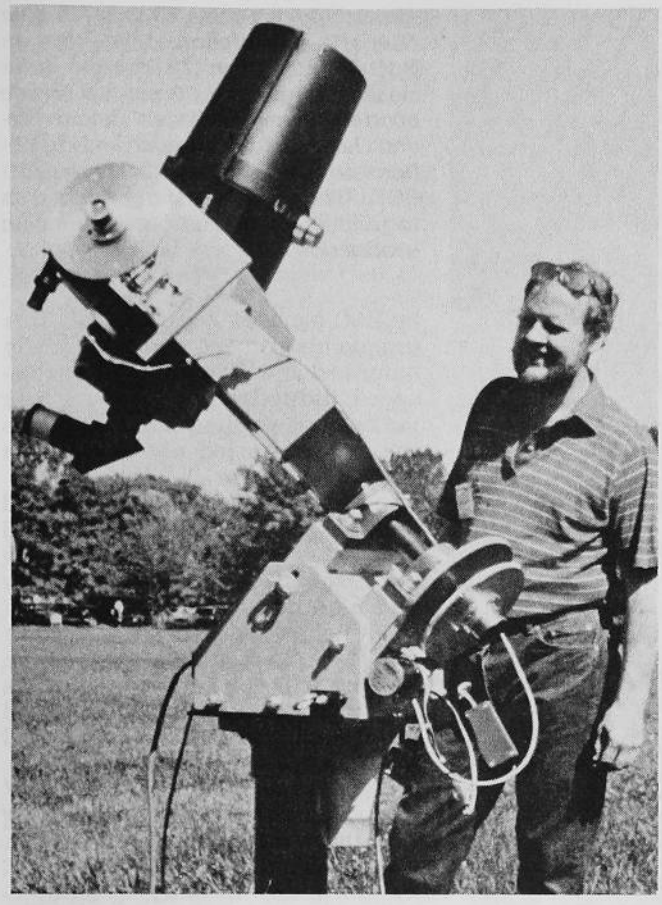
Bill Burton uses a surveyor's compass and inclinometer to aim his 17.5-inch Dobsonian. Note the handy observing table on the rocker box.

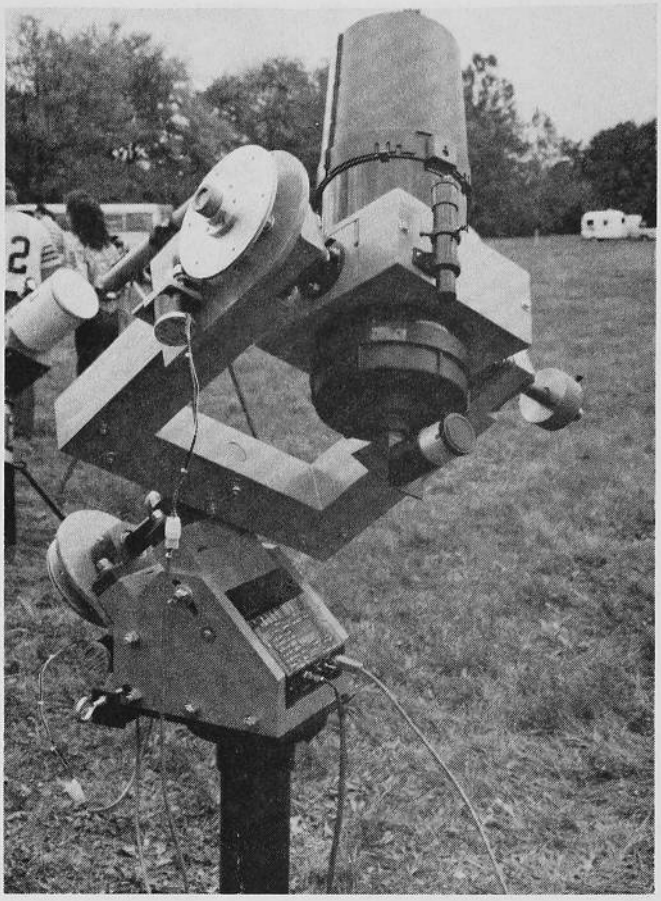
Dan McConaughy's fork-mounted equatorial is made of 1/2-inch plywood over a frame of 2x2s. The north polar bearing is a 15-inch disk.

The second item to catch my eye was a large refractor brought by Dan Rothstein. It towered over surrounding instruments. It was a 6-inch f/10 Jeagers lens set on an anodized aluminum equatorial mount, which was put on a heavy three leg oak tripod.

Size always catches the eye and the 17.5-inch fork-mounted telescope brought by Dan McComaughy of Evanston was large. It was a massive structure—striking it with a fist hardly made it vibrate and it quickly settled down. Overall it was a very stable structure. Large declination bearings and a rotating tube made observing convenient at all times.

The most massive and impressive telescope was a 16-inch compound instrument that could be used as a Newtonian or Cassegrain. It was

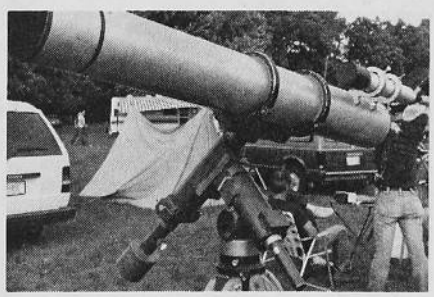




Robert Jakubowicz's commercially made SCT rides on a home-built computerized fork mounting. Stepper motors drive gears diirectly.

brought by Walter Piorkowski of Tinley Park, Illinois. It was shown in its f/5 Newtonian mode rather than in the f/20 Cassegrainian. Its outstanding feature was a massive mounting, a modified Springfield beavertail, but the fixed eyepiece capability was not used. The 3-3/4"-inch shafts carry the telescope tube without shake or vibration while attached to a 12-inch drive gear. Latitude and polar alignment are built in the base, but once mounted in a permanent observatory, they will not be needed except for an original alignment. An 8-inch guide scope was adjustable for either viewing or finding objects while a 15-inch tangent arm with motor control provides control of both axes while viewing. It was most impressive to see the van it arrived in, with its beam and chain hoist for handling the parts of the telescope and mounting them. The complete assembly weighed about 2,000 pounds. This was the last year it will be shown at Astrofest. Henceforth, it will be mounted in a permanent observatory and not moved again.

Seeing the heavens around a telescope tube always attracts attention and such was the case of the instrument of Roger Tanner from Canton, Michigan. The set of struts for his 17.5-inch Dobsonian was removable, so the top portion could be placed inside the mirror base to compact the unit for transportation in his Escort automobile. He found that wrapping the wooden struts with pipe insulation dampened vibration and stabilized performance. The "heavens" I'm referring to were a cloth wrapped around the tube. It was originally curtain material he obtained as a leftover. It now doubles as a light shield for his open tube structure. Even cloudy skies don't prevent one from seeing the sky with this instrument.

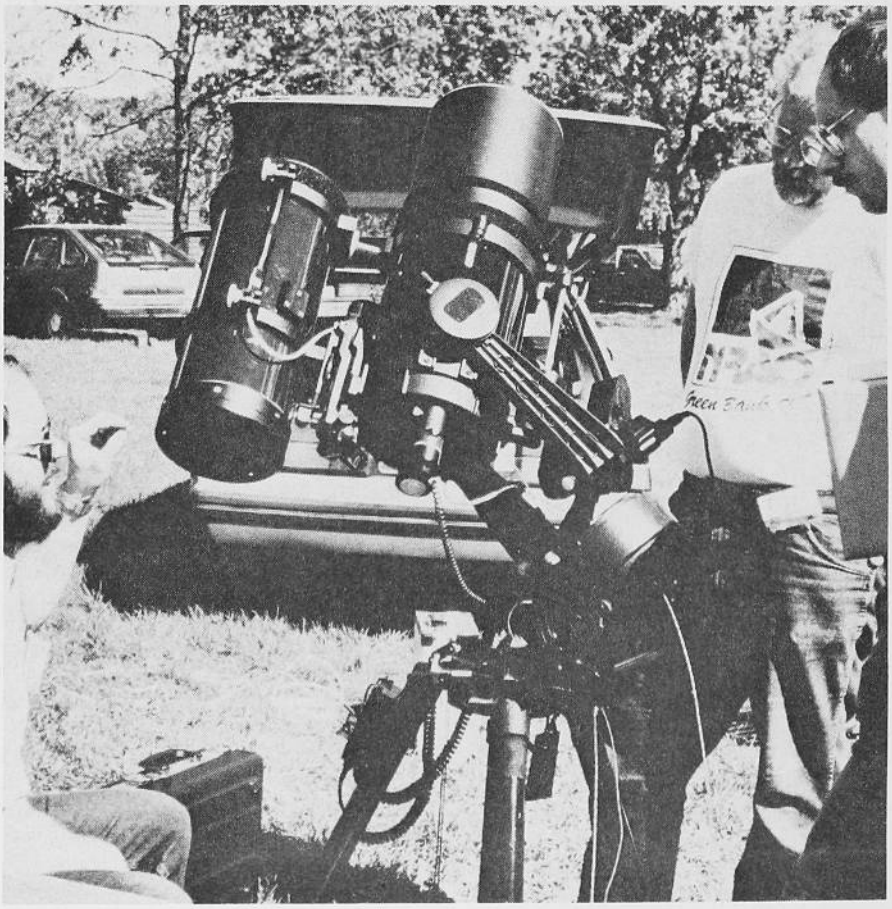


Dan Rothstein's 6-inch f/10 refractor rides on a homemade German equatorial mounting with heavy brakes. The objective was made by Jaegers.

A wooden split ring mounting was shown by Joseph DeHoff and Robert Rydorn of Bloomington, Illinois. The mount carried an 8-inch mirror for test purposes and display at the meeting but when finished will carry a 12.5-inch mirror. It has a very smooth rotating tube assembly at the top of its tube and by careful balancing of the weight and structure design the light plywood construction handled the operation of the mount adequately.

The past was shown by the Popular Astronomy Club, Inc., of the John Deere Planetarium, Augustana College, Rock Island, Illinois. Frank Haysbrook headed the club's restoration committee. On display at Astrofest was a restored 8-inch lattice-tube Newtonian made in 1934

"Heavenly" cloth cover blocks stray light. Roger Tanner's 17.5-inch Dobsonian collapses into a 23x23x17-inch box for transport in his car.



Above: James Pace's 10-inch f/6 blue "Berry" clone follows the plan in ***Build Your Own Telescope*** *quite closely. It sports a 60mm f/5 Meade spotting scope as finder. Below: Steven Lordcotton showed modifications to a conventional 8-inch f/10 SCT. "The objective of my mods was to reduce frustration and enhance a production scope," he notes.*

by PAC member August Wedt. This unique instrument was equatorially mounted and driven by a variable-speed induction motor. This took me back down the years– 1934 was the year I started my first 6-inch plate glass mirror.

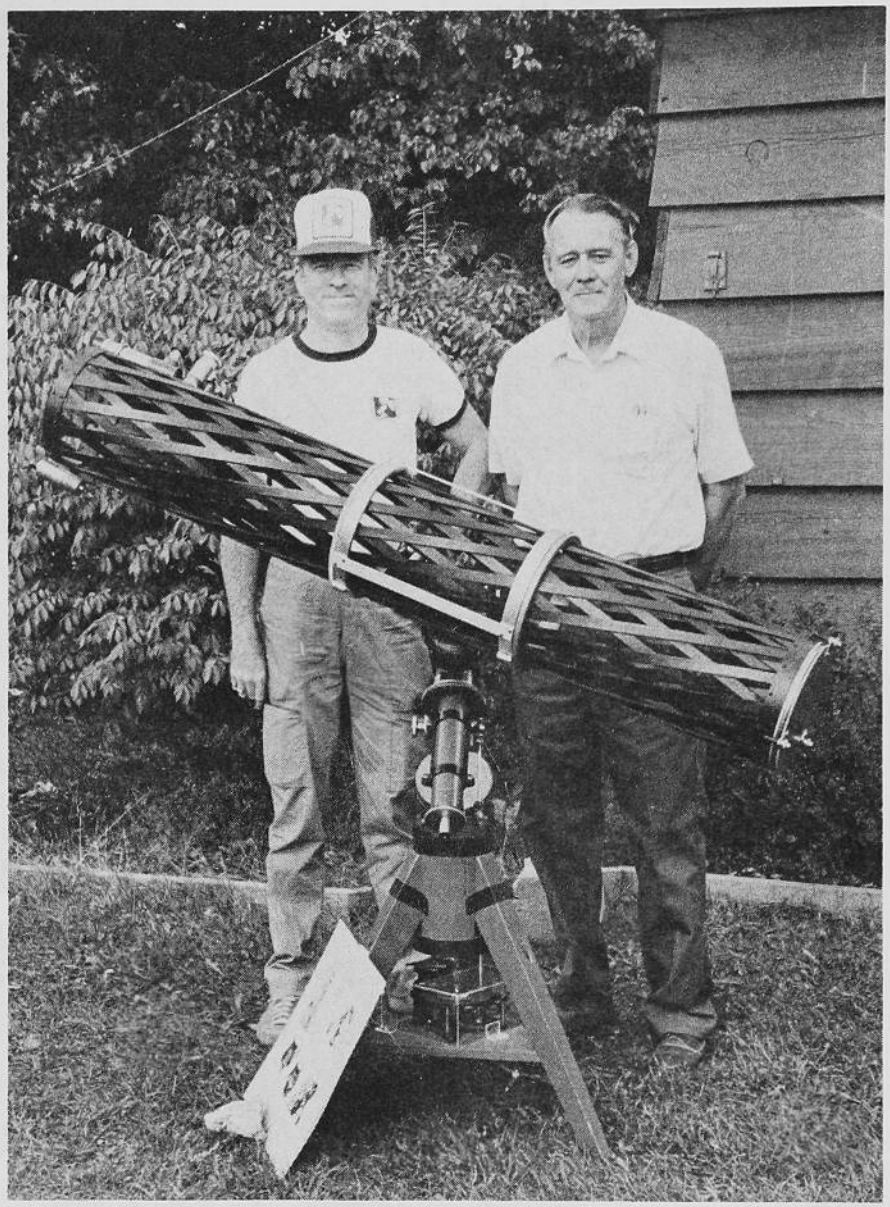
In the center of the telescope field I found Roland Christen. He had brought several of his amazing apochromatic lenses for display and nighttime viewing. He brought an 8-inch (which someone said was an f/14). On Saturday morning he was in the process of taking if off its equatorial mounting so he could display his latest 6-inch f/12 folded instrument.

The most exciting mechano/electronic display at the meeting was that of Bob Jakubowicz from Wheatfield, Indiana, who brought his fork mount with computer-controlled axes and automatic object finding by computer. The compact electronics fit in the base of the mounting, but he intends to compact it even further. He hopes it will eventually fit in the observer's hand. He and his brother designed all the electronics around a 8031 computer board that they designed and made themselves. They also wrote the program for storing and retrieving data and controlling the motion on the axes.

The telescope was not polar aligned during the day, but he ran the unit so one could see the fast action of the shafts on the mount. Object names and information are displayed now in a large red LED readout, but later in any hand-held unit it will use a liquid crystal display instead. For accuracy he has installed 360-tooth Byers gears on both axes, with stepping motors to control the movement. This was entirely a homemade unit independent of any commercial similar items now on the market. I was most impressed with its operation.

Weather is always a factor at astronomical meetings. One must always remember the old weather saying, "Clouds like crowds!" in outdoor activities. Astrofest was no

The Popular Astronomy Club of Rock Island restored this vintage 1934 8-inch Newtonian with a lattice tube. Drive is an AC induction motor.



exception: it was cloudy all the way up there and a light sprinkle was felt for a few minutes around 4 p.m. Friday night started cloudy, but as it became dark, word came that the sky was clearing and sure enough stars were seen between the clouds. By the time it was completely dark, the sky was clear, but it kept varying in a high cloud cover and some lower clouds so conditions were constantly changing.

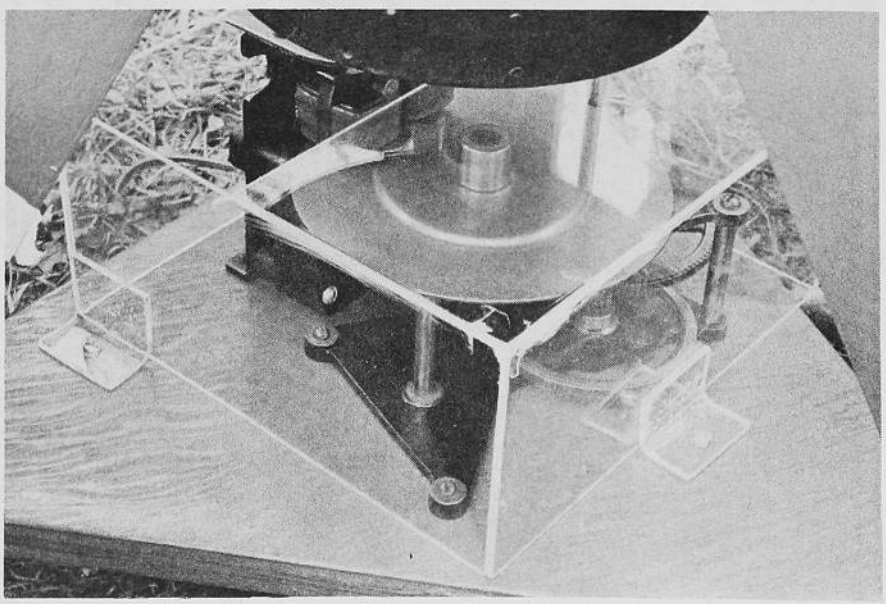
I took advantage of the clearing to take my special Pretoria eyepiece (see TM#29), and put it on a fine 10-inch Dobsonian. Before long a line had formed to view with it. Again I kept hearing the same phrase, "My next eyepiece must be one of these" and "I never saw such a field on an f/4.5 instrument!"

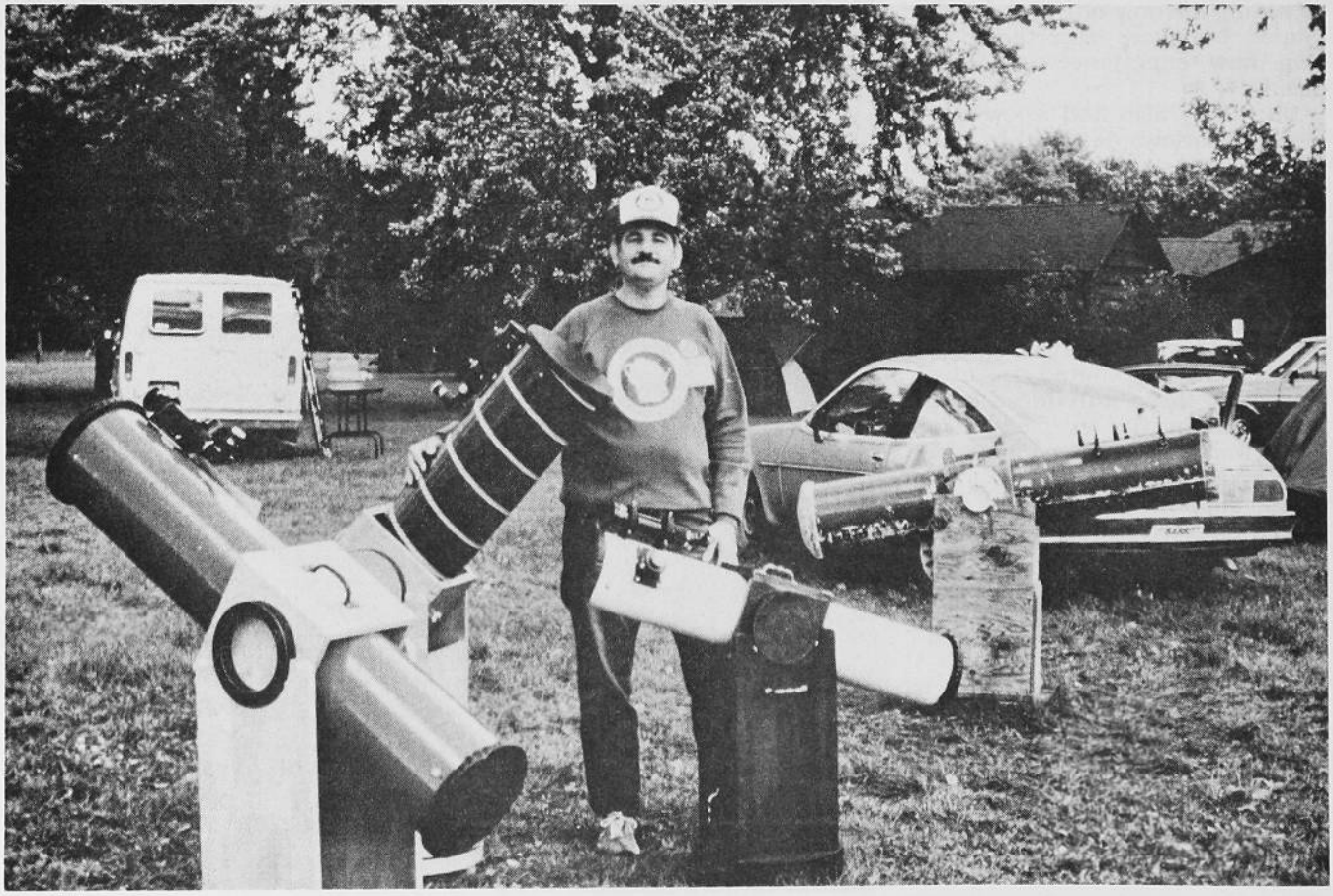
University Optics is putting this coma-correcting eyepiece for Newtonian telescopes on the market. Unfortunately the eyepieces were still in fabrication at Astrofest time, but they are expected to be available in 1988. Once they're on sale, I will no longer have the excitement of having the only one in the United States, but more important others can now experience its performance.

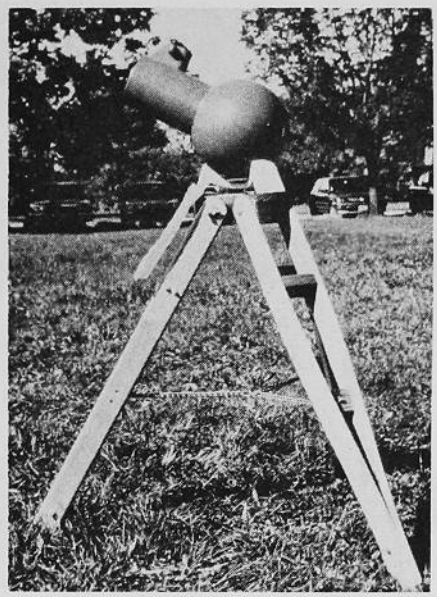
University also had a few of the new 3X Barlows designed by Heinz Klee of Pretoria. This three-element Barlow was designed especially for Newtonians and corrects sagittal and tangential coma from the mirror. It is corrected for spherical aberration, longitudinal and lateral color that the lenses might otherwise introduce. With this Barlow the only errors one should see in the image are those introduced by the residuals in the eyepiece itself. There were a few units on hand, and they went quickly. I understand that a good supply is in shipment.

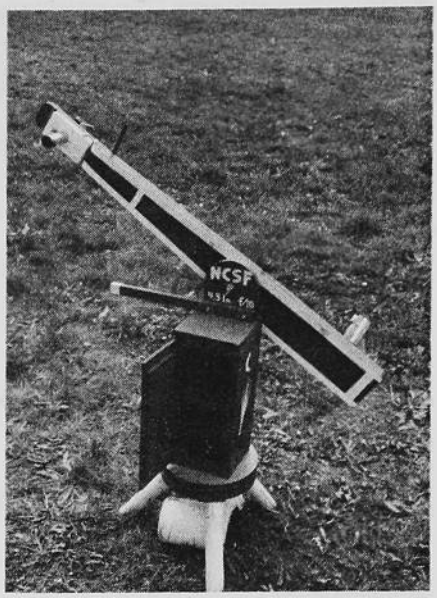
The weather continued to be variable. From 11 p.m. until 11:15 p.m. the sky became bad and it seemed it would continue to do so. Anticipating a busy Saturday, I retired to my sleeping bag. This was a mistake. At 11:30 p.m. Roland Christen arrived with his apochromatic telescopes and he set up the new 8-inch. It must have acted like a magic wand. The sky cleared and viewing was good for some time, but I was sleeping.

Saturday had clear skies in the









Left to right: Ron Ravenberg's "no tools" 17.5-inch Dobsonian was finely crafted. Paul Benesch showed a custom-built tripod for an Astroscan telescope. The tripod is oak. Kevin Bert and Gordon Guslick brough a home-made 4.5-inch Newtonina on a beam with a Dobsonian base and storage compartment for eyepieces, focuser, and diagonal.

daytime and I was able to look at the sun through the 6-inch folded f/12 apo with a Solar Screen. There was one easily seen spot; the image was razor sharp with maximum detail. I was anxious to use this scope in the evening because I had never had the opportunity to view through a Christen apo. Skies were cloudy at sunset but after the evening lecture and door prizes and awards word came that the sky was clearing. Everyone headed for the telescope field. I had to put the Pretoria eyepiece on a Dobsonian first to satisfy the requests of some, but as soon as I could I headed for the 6 inch f/12 apochromat.

It was on a starfield while waiting for temperature to stabilize in the assembly, but the sight of the needle sharp images it display against a midnight black background was most impressive. Even at low altitude the view of M22 was outstanding. When I suggested we view M11, my favorite low-power object, everyone exclaimed on the beauty of the sight. By this time Jupiter had cleared ground turbulence and was high enough to view.

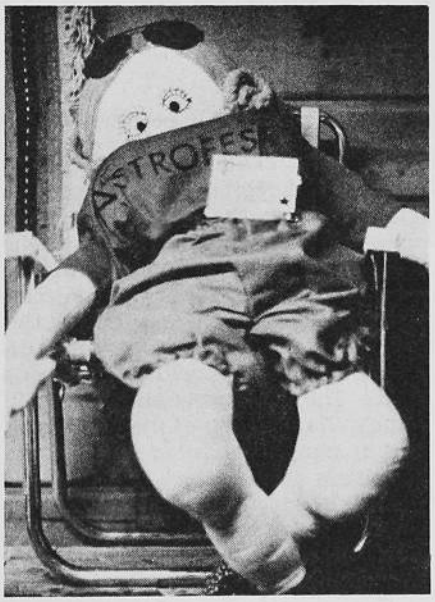
I had already looked through the 6-inch f/10 Jaegers lens at Jupiter and, although it was giving a good view, there was no comparison to the one in the apo. Jupiter and its four moons were as sharp and clear as I have ever seen them, even in an unobstructed reflector. Try as hard as I could, I saw no color in or on the edges of Jupiter. Contrast was high and belt detail excellent, with the weak faint Red Spot easily located on the disk. A 92mm f/7 Christen apo was also available and in spite of the fast focal ratio Jupiter showed no color, even when viewed with a 4mm eyepiece.

There have been reports of color in apochromatic lenses (see TM#31), but there are many things to be considered in discussing this. Even focusing matters. To obtain maximum performance, Christen asked everyone to refocus because even slight differences can introduce color due to a slight defocus. On a bright white star with high magnification one probably can see color, but it is so slight that only an expert would notice it. Many times such an expert would be using powers no practical observer would ever consider using except to test an objective. The last view I had of Jupiter was around midnight, when a satellite shadow was visible on its surface. The contrast of the shadow was something to see: it was so black it looked like an ink blot.

I intended to get up at 8 a.m. Sunday to drive back to O'Fallon, but it was 10 a.m. before I woke and looked at my clock and found a practically deserted telescope field. After washing up, I drove into Kankakee for breakfast and then headed back home after the best Astrofest ever.

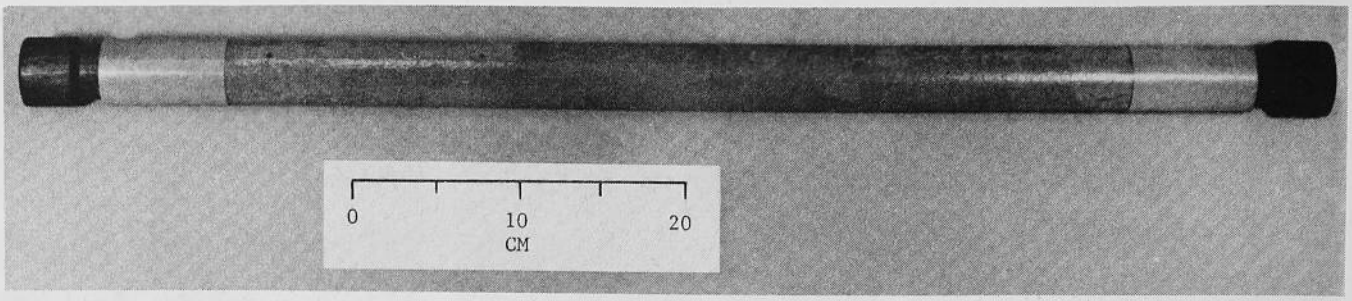
One final note: I'd like to thank Christine Hansley, Mike Barrett, and John Allseits for taking the photographs that accompany this article. My photos didn't come out—and TM would have been stuck pictureless without their help. Thanks again

—*Robert E. Cox*



"Jenny," the Astrofest mascot, is a member of the Chicago Astronomical Society. Does her name recall the Mount Jennings Observatory?

Above: Ronald Giles displays his twin car-mounted telescopes. Below: Frank Roldan stands with three Dobsonians built by the Milwaukee club.

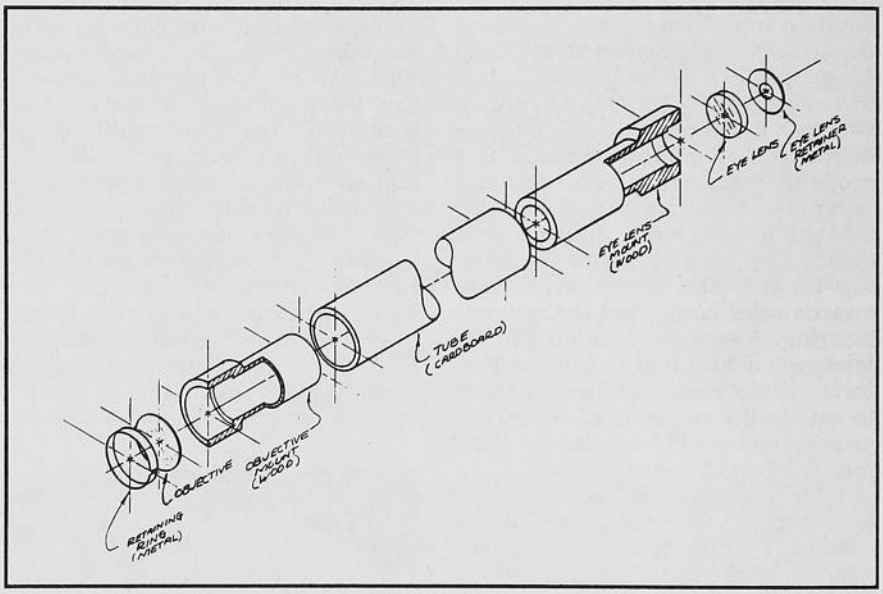


Build a Replica of Galileo's Telescope

Introduction

It is a rare person who doesn't feel a bit of a chill upon walking into the Air and Space Museum and viewing the *Wright Flier*, the *Spirit of St. Louis*, and the *Apollo 11* capsule. In a similar way, those of us who are interested in telescopes and astronomy usually feel a peculiar twinge when looking through a Clark refractor or some other early instrument. Yet at night we often gaze casually upon the very things that revealed so much to Galileo, Herschel, and others without considering the fact that we are touring a museum of ancient sights. We should reflect upon these things, especially when we bring Jupiter into view for a neophyte. As we explain that the image seen is the same as that presented to Galileo by his telescope, we feel some of the sensation of touching the piece of the Moon that is in the Smithsonian.

If you enjoy pondering such notions from time to time, you may wish to undertake the modest construction project described here. It will require little effort and hardly any money, yet it may turn you into a poet. It will enable you to see the sights Galileo saw, as Galileo saw them.

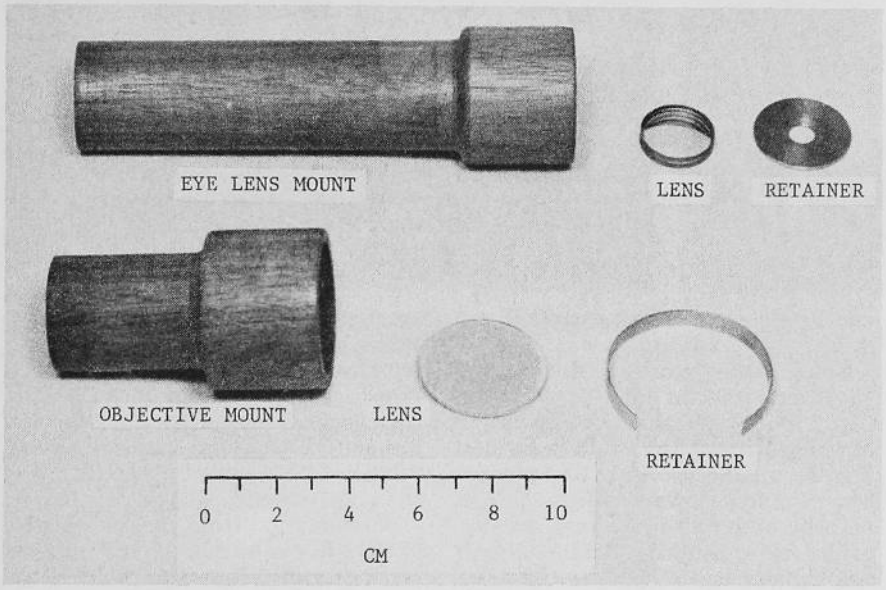


Building the Telescope

The telescope I built is nearly equivalent to Galileo's. The lenses that are specified approach the optics of Galileo's telescope but are very inexpensive. They can be obtained from Edmund Scientific and cost less than five dollars each. Construction of the telescope will hardly be a challenge to the experienced ATM. Enough detail can be gleaned from the figures to guide even the beginner. Of course, the ambitious builder can elaborate on the instrument to his taste. The general form is suggestive of the form and appearance of Galileo's telescope as described in Louis Bell's *The Telescope* and Henry C. King's *The History of the Telescope*, but it can be adapted to suit the materials at hand.

A Galilean telescope is particularly simple, consisting of only an objective and a single, negative eye lens. It produces an erect image but suffers from a severe limitation of field. Galileo probably carried the arrangement nearly to its practical limit of power. By most accounts, he made his principal discoveries with a telescope that magnified about 32 diameters. However, according to one of the foremost modern Galilean scholars, Stillman Drake, Galileo probably used an instrument of about 20-power with the objective stopped down significantly (see Drake's *Galileo at Work*, University of Chicago Press, 1978). The two lenses used in the replica yield an instrument of about 30 power. The lens diameters are close to those of Galileo's telescopes. An alternative eye lens could be selected to produce a 20-power version if desired. Whatever the actual case, the lenses specified here are sufficiently close to the originals to yield a reasonable approximation of Galileo's optical system.

The lenses I used used in my replica are Edmund stock numbers



A skinny tube with a lens at each end changed the course of astronomy—and revealed a larger universe beyond. Top: Two-and-a-half feet-long and an inch and one-half in diameter, Galileo's telescope was a "lightweight" by today's standards. Below: Turned hardwood components hold the telescope's two lenses. Lenses are secured by metal retainers, but a few drops of glue or O-rings would serve just as well.

A94,743 and A95,453 for the objective and eye lens, respectively. The objective has a diameter of 38mm and an 800mm focal length. The eye lens has a 23mm diameter and a focal length of -27mm.

The tube was made from a cardboard mailing tube of about 4.0cm outside diameter and 70cm length. Paper packing tape was used to trim the ends to improve the appearance. The tube was varnished on the outside and painted black on the inside. The lens holders were turned from hardwood to fit the lenses and to produce a smooth sliding fit with the inside diameter of the tube. The dimensions of these parts should be made to allow about 10cm of focusing travel by sliding both of the lens holders. With both lens holders inserted as far as possible, the lenses should be about 76cm apart. Such an arrangement will allow the telescope to be focused on nearby objects as well as on objects at infinity.

The objective lens is held in place by a retaining ring made from a strip of sheet brass. Any suitable means will do. A dab of glue, a rubber O-ring of the right size, or a piece of wire coiled into a circle are all reasonable alternatives. The eye lens could be secured by the same means. However, it probably should be stopped down considerably from its full diameter. Accordingly, the scheme shown in which a metal disk serves both to secure the lens and to stop it to about 6mm diameter is used. To reiterate a point from above, the construction details described here yield an instrument with the general appearance of the original, but are unnecessary from a functional viewpoint. The whole thing could be simplified by just mounting the objective directly in the tube and making a suitable eyepiece from the other lens. Of course the length of tube will have to be changed if this method is adopted.

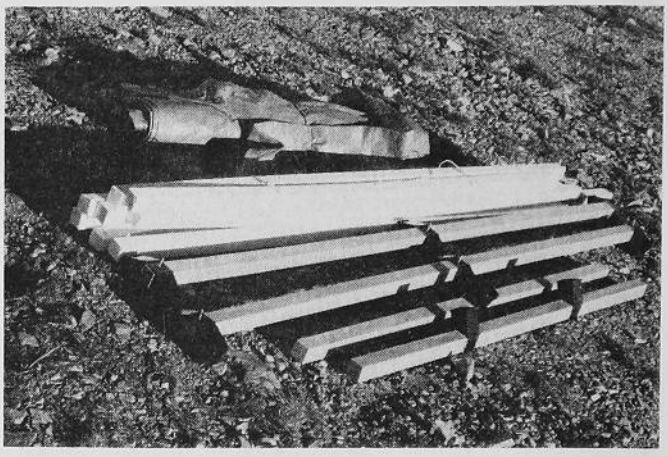
Using the Telescope

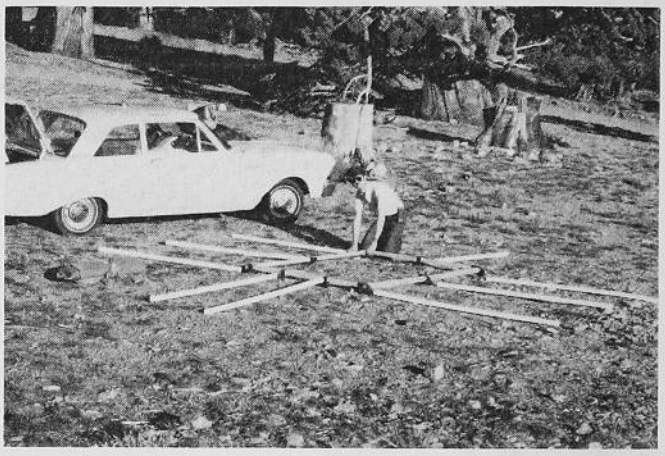
As mentioned earlier, a telescope of this type has a very limited field of view. This characteristic makes locating objects much more difficult than might be expected with a 30-power instrument. Some sort of mount is essential—at least a good camera tripod. I use a simple wooden cradle and rubber bands to support the telescope on a camera mount.

Building this instrument is fun and nearly everyone will be curious to take a look through it. Using it affords a special opportunity to wax philosophical, as suggested earlier. It may also teach a lesson. In this regard we have all read that early man learned to make fire by rubbing two sticks together. It is safe to say that anyone who would write such a thing has never tried to start a fire that way. We have also read how Galileo demonstrated his telescope to a group of dignitaries and how some of those who looked through it reported they had seen none of what Galileo described. In relating that episode, authors usually imply that those individuals were hard-headed, dogma-bound ideologues who refused to believe their own eyes. It is more likely they had really seen nothing. Authors who take an uncharitable view of those events have probably never tried to use a telescope of this type. They probably never tried to start a fire with two sticks either. Be prepared.

Cecil O. Huey, Jr.
414 Pendelton Road
Clemson, SC 29631

Home-Made Portable Observatory Makes Photography Jiggle-Free





After a year of many trips to my favorite mountaintop observating site with a 20 percent abort ratio, most often caused by wind, I began searching for a portable observing shelter. I saw ads in the popular astronomy magazines and decided some of the shelters shown were pretty nice. I also decided the expense was unjustified.

But after two more aborted trips (it takes about 2.5 hours to get far enough from the lights of Los Angeles), I was getting fairly desperate.

It was then I saw something in the local household improvement store. It really caught my attention. A tent maker I'm not, but I decided to give it a try.

After all the expenses were added up, I found that only three aborted trips would pay the $60 my new structure would cost. It took about three weekends and four evenings to finish it up.

Upon completion, I found I was enjoying my nights at the scope a whole lot more. I was warmer and actually had a place to set the large array of gadgets and accessories I had accumulated. The optics were staying cleaner, and the occasional car lights were staying out of my eyes.

Now, what exactly did I put together? As you look at the pictures, you'll see a setup sequence starting with the unassembled bundle on the ground ready to go. The next few views show the set-up step by step, with one man raising of the frame, and the details of field assembly.

The frame components are inserted into a plastic "Tinker-Toy" pieces; these are what spurred my idea. The kit I bought is set #0300 from Frameup Inc., P.O. Box 75, Stevensville, MT 59870.

The frame uses 2x2 lumber cut to the appropriate lengths to accommodate the type and height of your telescope. For my 10-inch Schmidt-Cassegrain I set the dimensions so I have access to within 30 degrees of the east-ern and western horizons. I also have access to the Lagoon Nebula to the south, and if I need more, I can raise the tripod.

I made the skin of the observatory from a 16x20 foot tarp. I laid out the pattern on paper ahead of time and then drew the pattern out on the tarp. The skin was patterned in such a way to give an inch and a half overlapped hem around the edge for strength around the edges. After cutting it, I put brass eyelets in. These are sized so as to produce a hole large enough to allow 10x24 hanger bolts to be inserted. Wing nuts hold the skin to the frame, as the picture detail shows.

The setup time was initially twenty-five minutes for one person, but I've found that after some practice it goes up faster. In my opinion, the setup time is completely justified by the shelter's usefulness.

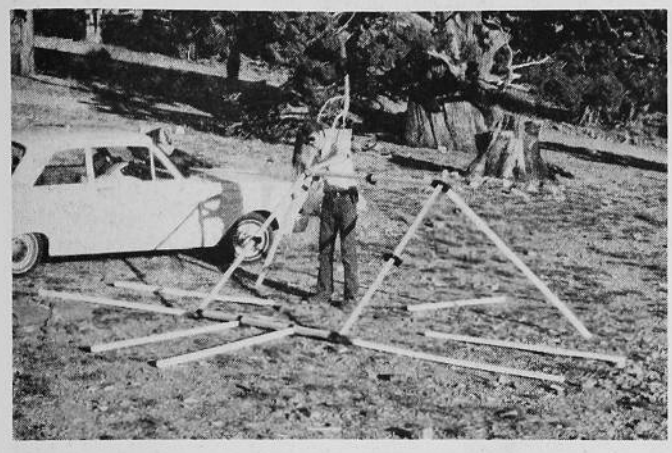
The last photos show the observatory in use. The unit includes a roof if you want a private tent or, if it rains, a dry place for the equipment.

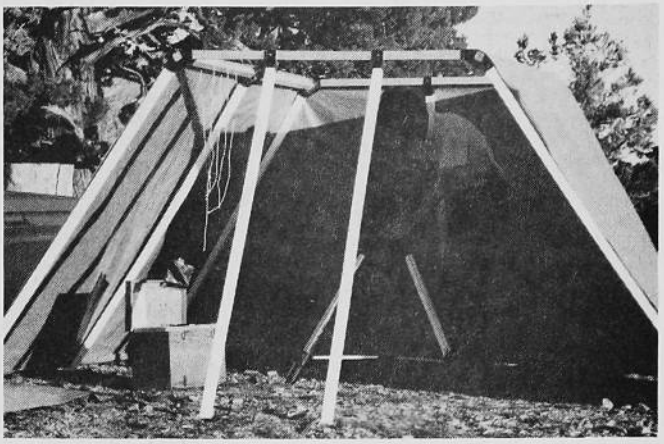
I hope this experience of mine will spur others to build their own little environment and take some of the chill out of this fantastic hobby.

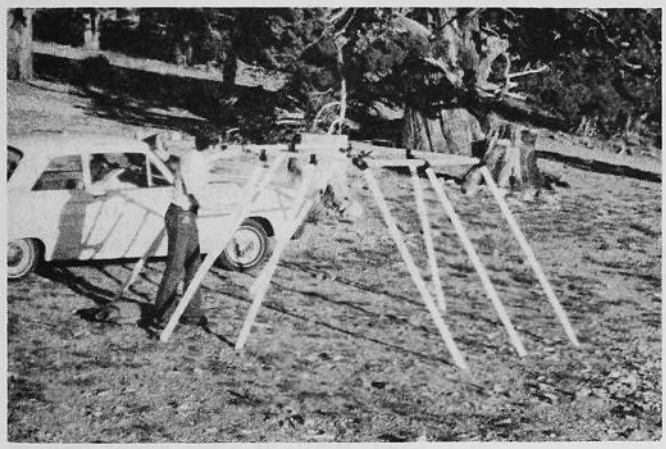
Oh, the wind problem? It doesn't bother me anymore, well at least up to 15 to 20 miles per hour. Before, I would not have even attempted any photography at all.

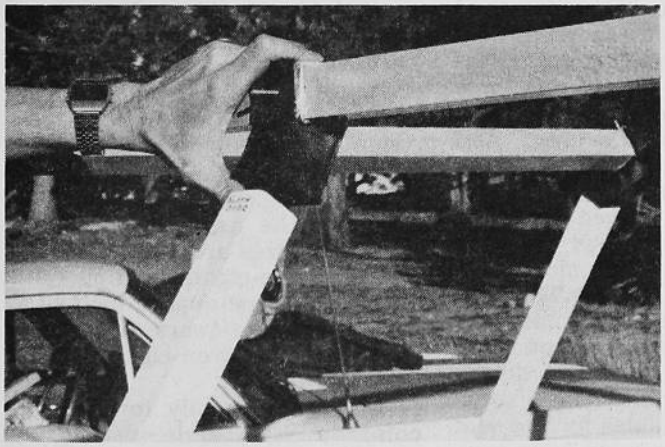
Good luck on your version.

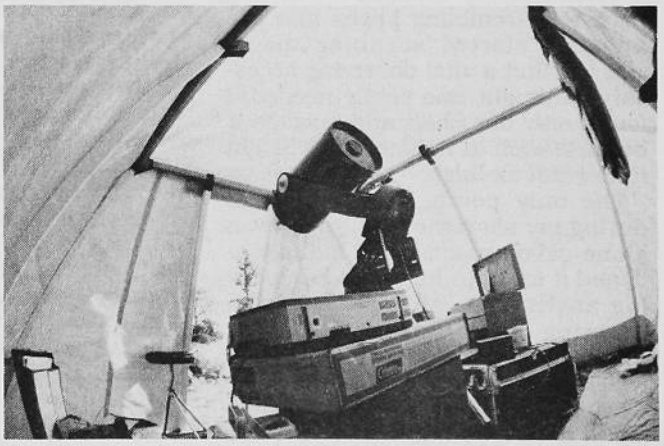
Ernie Williams
247 "B" North Mountain Trail
Sierra Madre, CA 91024

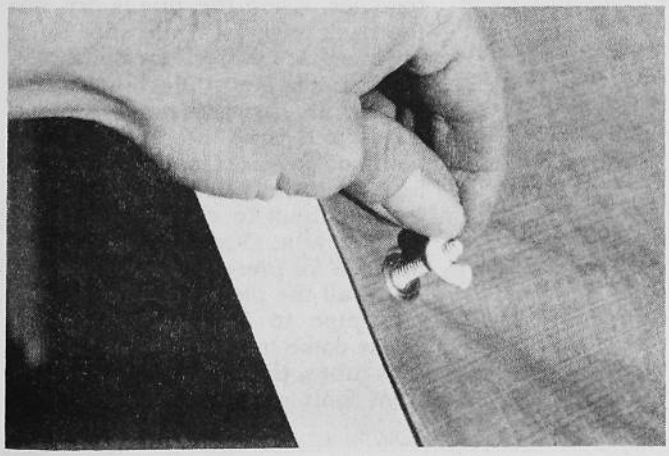






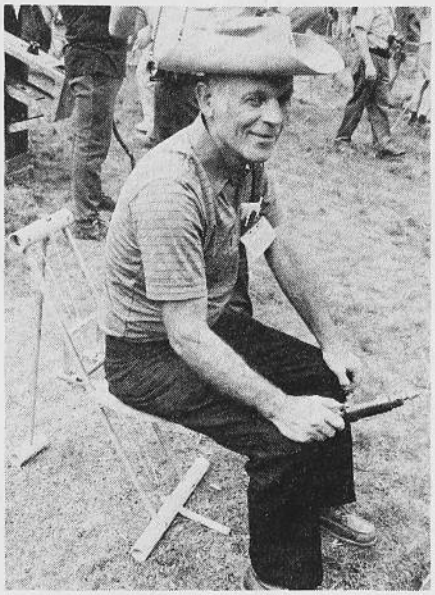






STOVE

This Adjustable Chair Makes Observing Easier and More Comfortable



The fellow in the ODYSSEY I brochure looks well over six feet tall, but he seems quite comfortable looking into the side-mounted eyepiece. He's sitting on a standard folding chair and leaning slightly forward to use his telescope. My first night with my Dobsonian was a revelation. I discovered the inability of any chair to accommodate my body comfortably.

When I finally brought my aching back and trembling knees into the house, I started scanning magazines to find a vital observing accessory I thought was sorely needed. I found only one chair and rejected it because even at its minimum height it was still too high.

The only perch I had available during my short viewing career was a one-gallon paint can. I had abandoned it for both high and low viewing angles and, all too often, was teetering over onto the wet grass. These are not conditions under which one enjoys a hobby.

I decided it would be very desirable to have an adjustable chair. The seat would have to move up and down, and it would have to be easy to move forward and backward on rough ground. This would go along with light-weight and a freely moving seat assembly. Freely moving meant controlled friction, because it should be far from freely moving when a person's weight is on it.

Thinking back to the time I built a hatchway in a cellar wall and added a set of stairs, I was amazed to find that without being fastened to the wall or floor the stair remained remarkably stable even while I carried heavy articles in and out. (This was true, of course, only as long as I was careful to minimize vibration.) Mother Nature had thus conveniently equalized the leaning force with the sliding friction. I soon got over that joy of discovery and yielded to the lamentations of my wife who had more faith in lag bolts.

The chair that evolved from this thinking has three legs made of lightweight tubing. This material is electrical conduit and called half-inch although the outside diameter is actually closer to three-quarters of an inch. Two legs slope downward and are parallel. These serve as supports and slides for the seat assembly. They are bolted into two lengths of one and one-half inch PVC, which serve as the front footpiece and top rail. A single rear leg slopes backward only slightly.

The seat is made of two thicknesses of pine. The boards are glued together with the grains perpendicular. A group of pipes is assembled as shown in figure 1 and bolted to the seat. The distance between the top and the bottom friction bars is much smaller than that between the bottom one and the point where your weight will be centered. The ratio of the two distances is the factor by which the friction will be magnified by your weight on the seat.

Early experience has taught me that the friction may decrease rapidly if the seat is allowed to tilt sideways. The addition of the rectangular brace in the rear prevents tilting. If you inadvertently push the brace back, though, you will take a trip. As a safety measure, I added a nylon cord. While it adds slight friction during height adjustment, it greatly reduces the likelihood of accidental release.

Construction

Using a drill press will help greatly in getting things to fit together. Beg, borrow, or steal one to make the assembly pleasant. Four drill sizes are needed for this project: a one-eighth inch pilot drill for all holes, one-quarter inch for all bolt holes, three-quarter inch for all leg holes, and seven-eighths for the front foot hole.

The seat is easily formed with common handtools and glued together. When the glue is dry, use the back edge as a reference to lay out a square pattern for bolt holes. Your accuracy determines how closely it fits the main support tubes and thus affects the alignment of the seat assembly to the legs. Drill the four holes and countersink them to clear the carriage bolt heads. Varnish is recommended for preservation.

Cut all the pieces made of tubing and pipe to the lengths shown. These come in pairs: the main support tubes, the friction bars, and the front footpiece-top rail. The easiest

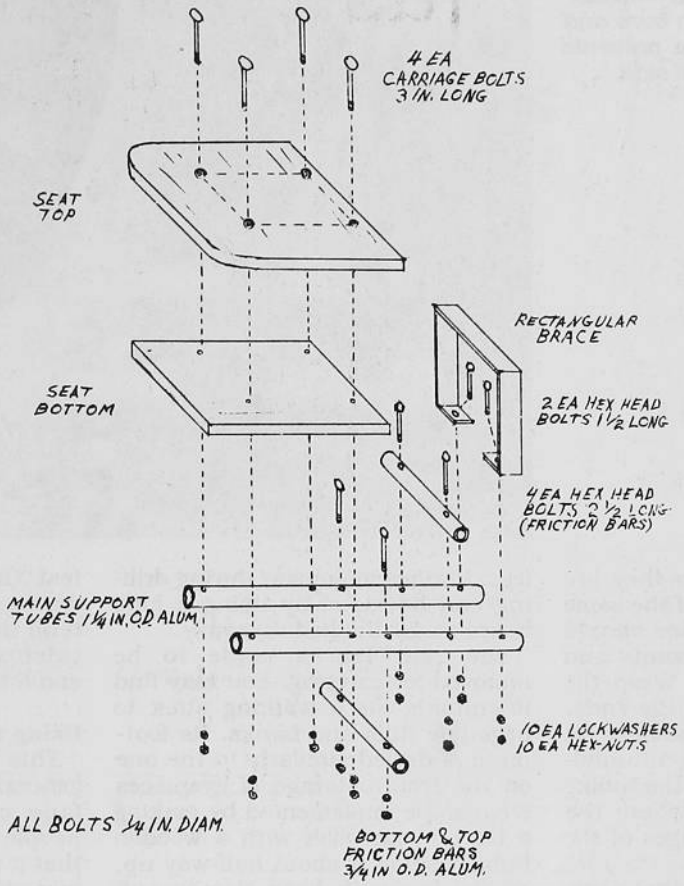


FIGURE 1
SEAT ASSEMBLY

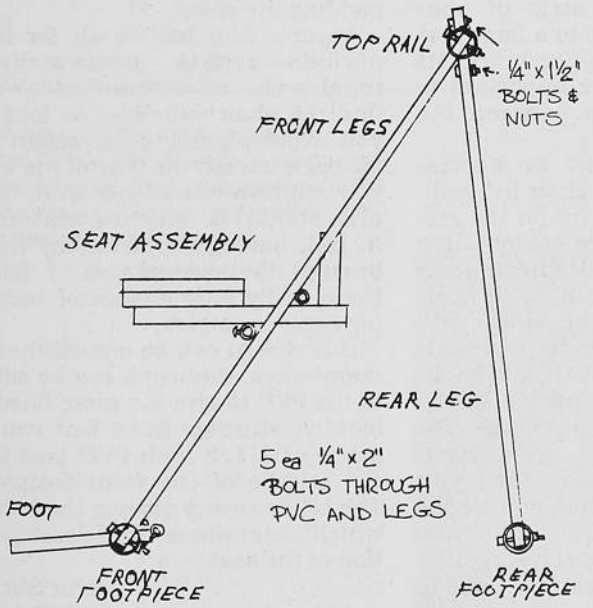


FIGURE 2
SIDE VIEW

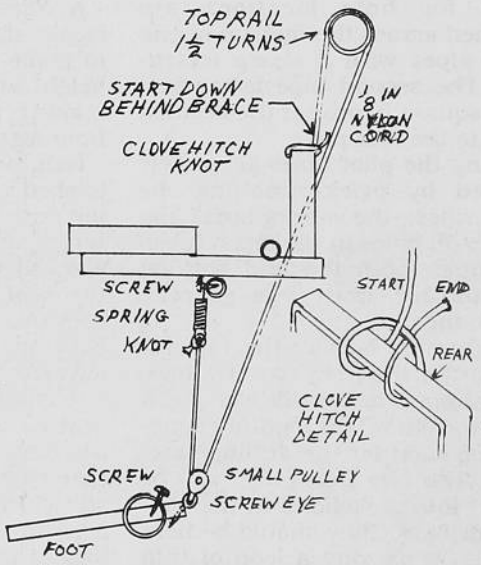
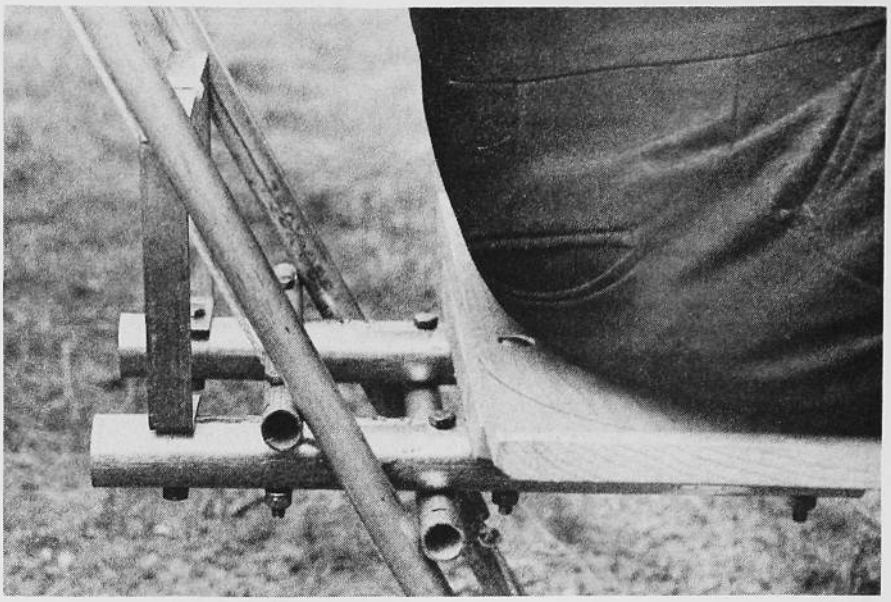


FIGURE 3
SAFETY CORD DETAIL



Side view of the adjustable seat. Position depends on friction between the bottom and top friction bars and the front legs. The brace prevents the seat from tipping to the side.

way to drill the holes so they are aligned is to tape pieces of the same length together. The latter should be marked at their midpoints and aligned at these marks. Wrap the tape around double near the ends, keeping clear of hole locations. An additional wrapping near the middle of the pieces will keep the tubing level for all holes even where the tubes project past the edges of the drill press table.

Mark the midline of the parts using black felt-marker in a broad swath down their lengths, and then scratch through the marker ink by dragging a straight-edged piece of metal along the inked areas while kept in contact with both tubes. Marks for hole locations are scratched across the midline of one of the pipes with a sharp instrument. The second pipe is marked with a square to project the location across to the first pipe.

Drilling the pilot holes accurately is aided by prick-punching the points where the marks cross the midline. All holes in the metal tubes go through both top and bottom; those for the front legs go only through the top.

The rear leg hole in the top rail and that for the front foot will have to be aligned and drilled using a protractor. They will require clamping in position for the drilling operations. The two front legs will be inserted into their holes in the PVC before drilling. They should be held in place by passing a loop of thin rope through the footpiece and top rail and pulling them together tightly with a knot. The holes will pass through both the PVC and the legs. Vertical alignment during drilling can be aided by using a long board under the tied assembly.

The rear leg is made to be removed for carrying. You may find it suitable for a walking stick to negotiate hills and banks. Its footpiece is drilled similarly to the one on the front. Storage of eyepieces etc. can be implemented by making a Lazy Susan disk with a wooden hub. Position it about half-way up, on the leg, with hose clamps and washers above and below. It can be tailor-made for your paraphernalia with holes or attached cups. Some means of retaining the stored items will help protect them should it get knocked over.

A one-inch wide strip of one-eighth steel is formed in a large vise to make the rectangular brace. Its height and width are important in making it reach up between the front legs.

Height adjustment is accomplished when off the chair by pushing down or pulling up on the rectangular brace. Once seated on it you will quickly learn to manipulate the seat by tipping it backwards slightly, grasping the sides with both hands and leaning your body forward. If you tend to fall backwards after leaning, quickly let the seat go up and it will lock in. The friction can be controlled to your taste by the amount that you stretch the spring when you tie the cord to the top of the rectangular base. I used a spring three eighths of an inch in diameter made of #17 gauge wire and about an inch long when relaxed. If in doubt, buy two or three sizes at a hardware store and test them to your satisfaction. A spring can be shortened by cutting it on the corner of a grindstone and twisting two loops out at the new end for attachment.

Using the Chair

This observing chair met with general approval at the 1987 Stellafane convention, although some people seemed to be concerned that it might be too flimsy. True, the materials are flexible, but they have been proven quite durable in many projects. It is not an easy chair but a convenient platform for comfortable viewing at seat heights between six and twenty-six inches. Further comfort can be obtained through padding the seat.

Anyone who has to sit for long periods—artists, birdwatchers, repairmen, or astronomers—will find the chair valuable. As long as you avoid placing your weight too far back toward the rear of the seat, you will have confidence in it. Children should be watched while usin it, but, having slipped many times during its development, I found there really little chance of squeezing heels or fingers.

This design can be embellished in many ways. End caps can be added to the PVC to give it a more finished look. A sturdier front foot can be made of 1-1/2 inch PVC teed into the middle of the front footpiece. The latter means moving the pulley, which determines the lowest position of the seat.

John Shelley
P.O. Box 185
North Granby, CT 06060

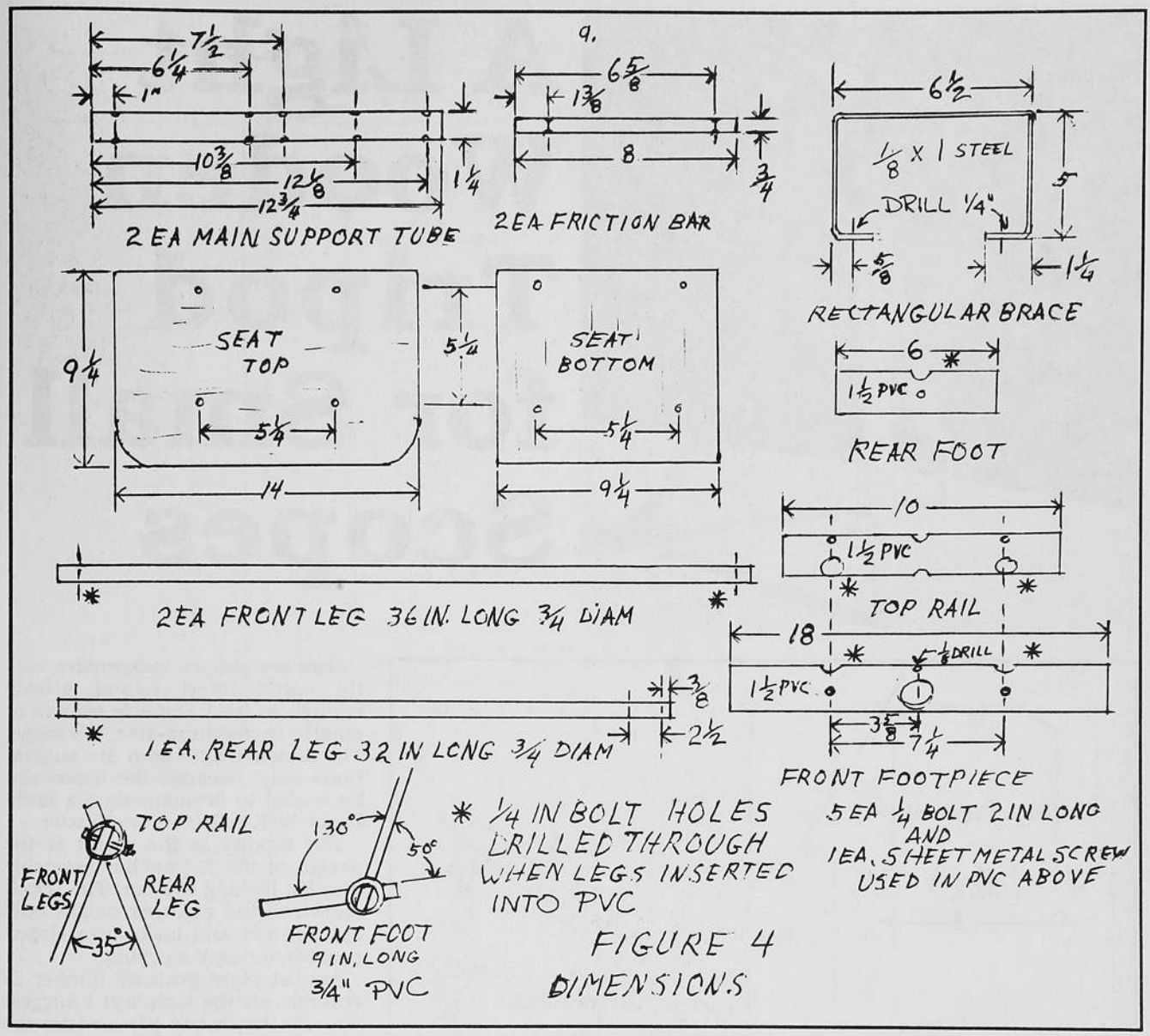
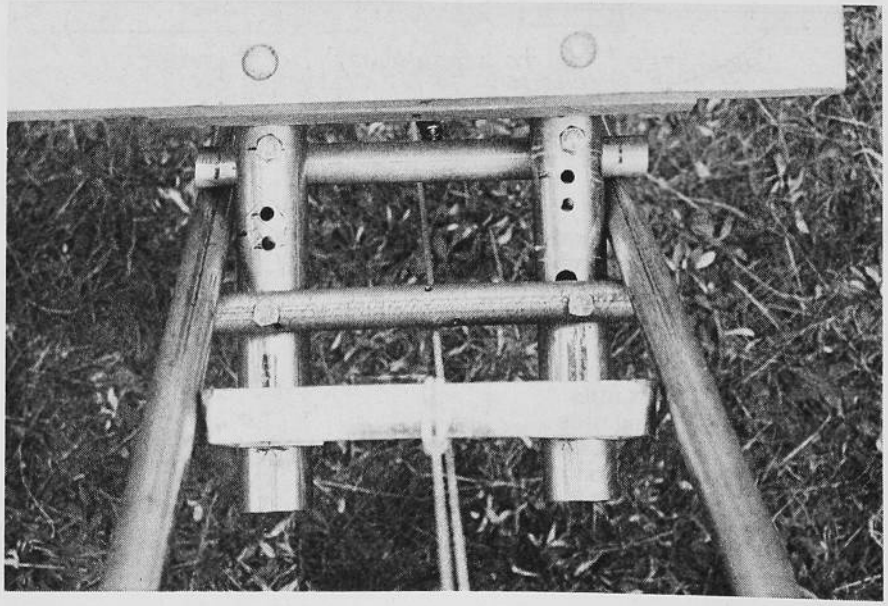
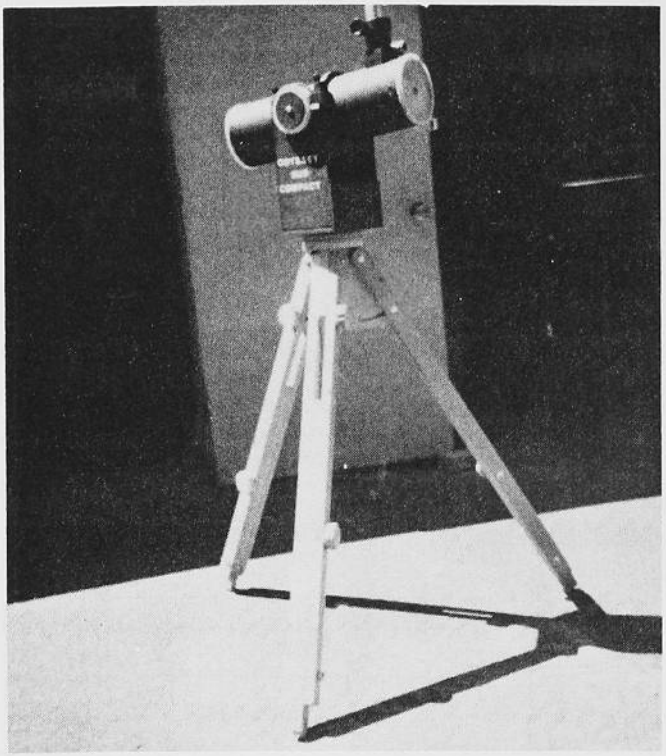


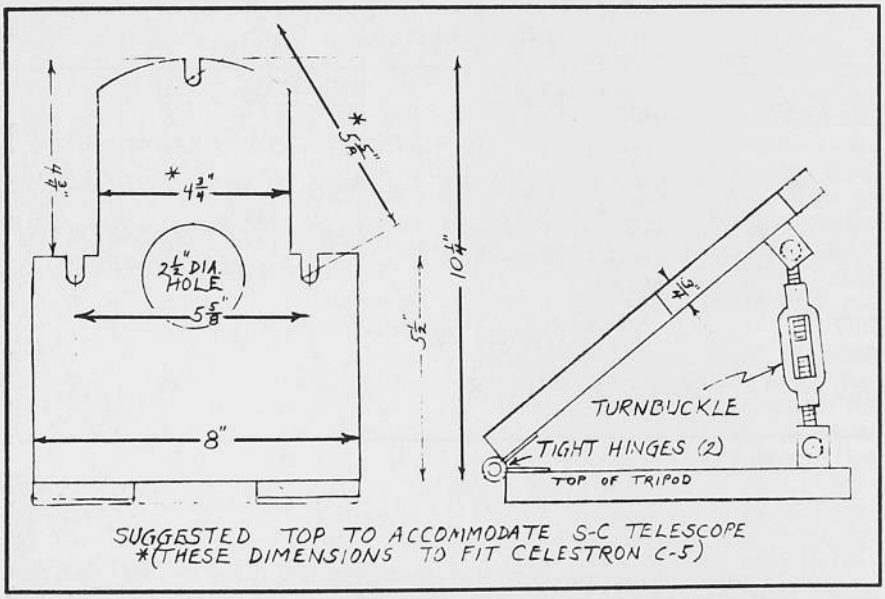
FIGURE 4
DIMENSIONS

Top view of the seat assembly and brace. Note the Nylon cord to prevent the seat from suddenly sliding to the ground! Tube material is inexpensive electrical conduit.





A Light Wooden Tripod for Small Scopes



SUGGESTED TOP TO ACCOMMODATE S-C TELESCOPE
*(THESE DIMENSIONS TO FIT CELESTRON C-5)

Bill of Materials

Approximately 2-1/2 square feet of 3/4" plywood
36 feet 1" x 2" finish lumber
6 each 1/4"-20 x 3-1/2" carriage bolts
6 each 1/4"-20 x 2-3/4" carriage bolts
6 each 1/4"-20 x 3/4" T-nuts
3 each 1/4" lock washers
3 each 1/4"-20 hex nuts
3 each 1/4"-20 wing nuts
9 each 1/4" fender washers
3 each nylon bumpers
12 each 2" wood screws (or enough 1/4" dowel for top and leg-anchor assembly. Use screws for top.)

Here is a simple, inexpensive, easily constructed tripod sturdy enough to hold any size camera or small- to medium-size telescope. The dimensions shown are suggestions only, because the tripod can be scaled to accommodate a fairly heavy SCT, reflector, or refractor.

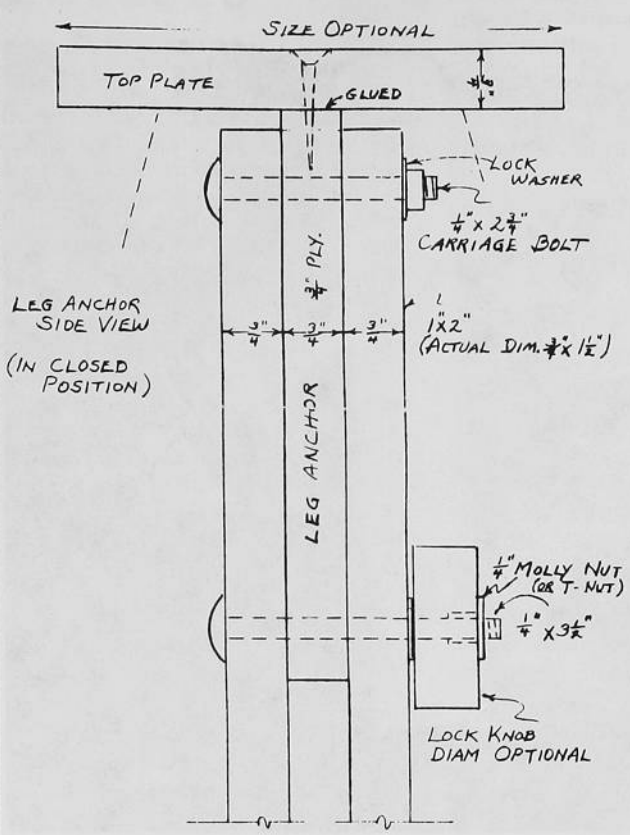
The rigidity is the result of the design of the leg anchor assembly and leg-locking system. The tripod shown in the pictures weighs only 8.5 pounds and locks in a closed position for easy carrying.

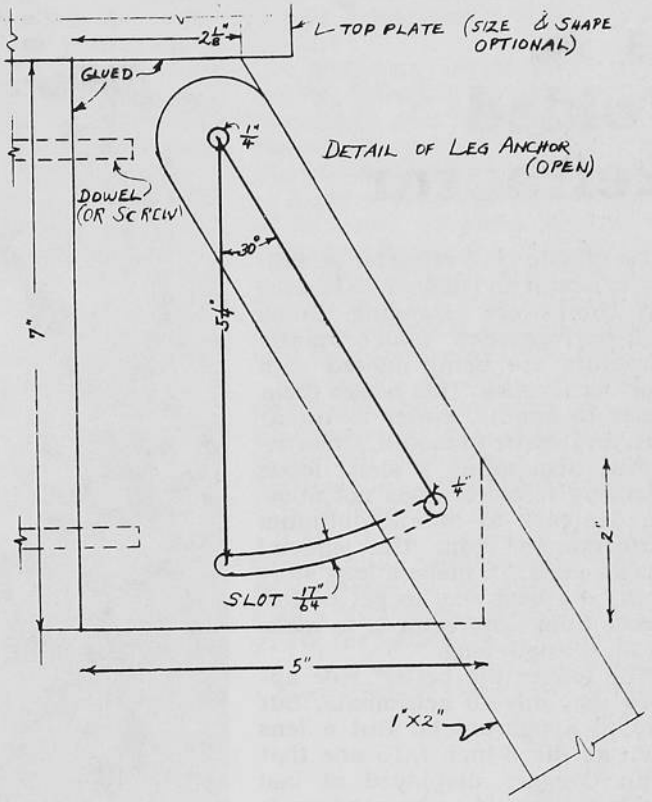
Any straight-grained lumber is suitable for the legs, but I suggest you use hardwood plywood for the leg anchor assembly. The top plate can be any size or shape, according to your needs, and can be adapted to have a built-on wedge or any other arrangement desired. Lumber and hardware are readily available. The total cost of the project should be less than a good eyepiece.

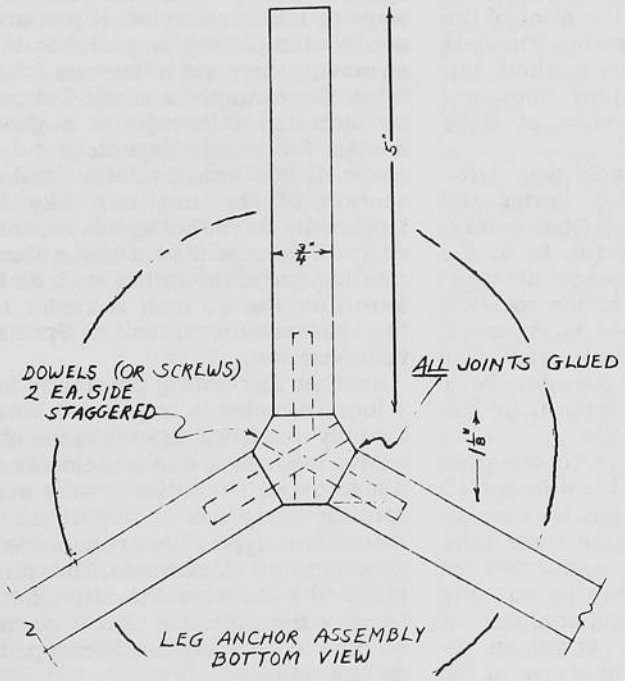
Though the tripod can be constructed with a power drill and saber saw, it is easier if a table saw is available to cut the slots for the extendible lower legs.

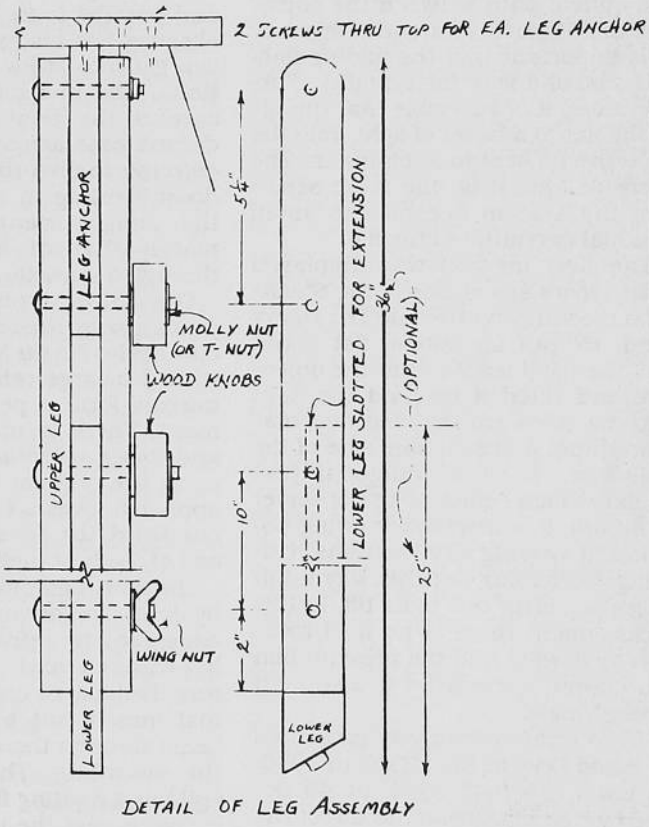
The drawings show all the important construction details, and the photos show how the finished project looks. I have used my tripod for over a year now, and find it very sturdy and durable.

Walter R. Coggan
5407 5th Avenue NE
Seattle, WA 98105

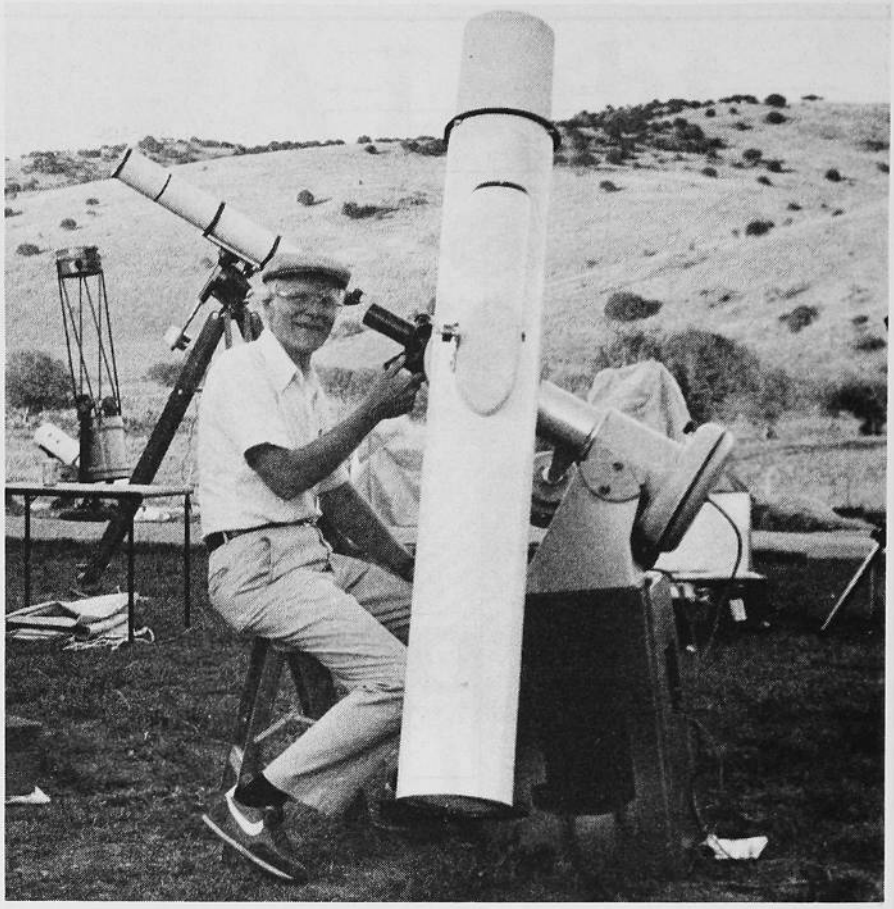

SIZE OPTIONAL
TOP PLATE
GLUED
LOCK WASHER
¼" x 2¾" CARRIAGE BOLT
¾" PLY.
LEG ANCHOR
LEG ANCHOR SIDE VIEW
(IN CLOSED POSITION)
¾"
¾"
¾"
1"x2" (ACTUAL DIM. ¾" x 1½")
¼" MOLLY NUT (OR T-NUT)
¼" x 3½"
LOCK KNOB DIAM OPTIONAL


2½"
L TOP PLATE (SIZE & SHAPE OPTIONAL)
GLUED
DOWEL (OR SCREW)
DETAIL OF LEG ANCHOR (OPEN)
1"
¼
30°
5¼"
7"
¼"
2"
SLOT 17/64"
5"
1"x2"


5"
¾"
DOWELS (OR SCREWS) 2 EA. SIDE STAGGERED
ALL JOINTS GLUED
1⅛"
2
LEG ANCHOR ASSEMBLY BOTTOM VIEW


2 SCREWS THRU TOP FOR EA. LEG ANCHOR
LEG ANCHOR
5¼"
MOLLY NUT (OR T-NUT)
WOOD KNOBS
UPPER LEG
LOWER LEG SLOTTED FOR EXTENSION
36" (OPTIONAL)
10"
25"
2"
WING NUT
LOWER LEG
LOWER LEG
DETAIL OF LEG ASSEMBLY

Portability Is A Folded Refractor



The classic f/15 refractor is difficult to mount and difficult to handle. But things are changing. Some high-performance apochromatic refractors are being offered with short focal ratios. This makes them easier to handle, easier to transport, and easier to mount. Unfortunately, demanding a short focus from any refractor does not allow the designer to obtain optimum performance from the special glasses used. To make a long story short, the best way to get performance from a refractor is to make the focal length long.

"The longer the better" rule applies not only to achromats, but also to apochromats. But a lens such as the 8-inch f/15 one that John Gregory displayed at last year's TSP would be horrendous to handle.

The solution is a simple one: fold the optical path between the objective and its focal plane with mirrors. It is important that the folding flats must be of a very high quality. Furthermore, it is advisable that the tilt of the flat to a beam of light from the objective be kept to a minimum. The more oblique it is, the more sensitive the system becomes to small residual curvature in the flat.

The first method was displayed many years ago at one of the Stellafane meetings by the late Dr. Henry Paul. He put an optical flat about half the focal length from the objective and tilted it to send the light path back toward the objective, displaced just a little to one side of the objective. A small diagonal just ahead of focus enabled the observer to obtain a comfortable viewing position at varying sky locations. Utilizing the folding flat this way minimizes any error due to its tilt. In this arrangement there is no field rotation in viewing and the presentation is a normal one relative to a straight through view.

The second system was presented by David Levy at the RTMC in 1980. He used two flats, each at 45 degrees to the light beam, to direct the original light path sideways and then alongside the original path and parallel to it. But because the observer has his back to the sky, he can get into awkward viewing positions. The observer must also be careful the heat from his body doesn't pass across the front of the objective to disturb seeing. The field doesn't rotate in this method, but the image orientation does not match that of a view straight through a refractor.

The third approach was tried years ago by Russell W. Porter, and also at the Pic du Midi Observatory to fold a large refractor. In it, the mirrors form a periscope arrangement. There is no image rotation and image orientation is the same as at the original focal plane. This approach gives a tube length about one-third the focal length, and is one of the best methods.

The fourth method is the one used by John Gregory on his 8-inch f/15 apochromatic refractor. By carefully arranging and tilting three mirrors, he has not only compacted the instrument but has also run the beam through the rotational axes of the mounting. This approach results in a rotating field of view at the eyepiece, and the image orientation does not match one at the focal plane of a straight through view. However, it offers a major advantage: a fixed eyepiece position. One can sit down to observe.

These are by no means the only ways to fold a refractor. If you are not contemplating a portable instrument, there are numerous solutions. For example, a single-flat polar-mounted telescope is a good design for a fixed-eyepiece telescope. It has image rotation and a section of the northern sky is blocked by the building it is mounted to. Or one can consider a fixed rotating turret mounting such as is found on the 10-inch refractor in the Hartness instrument at Springfield, Vermont.

Another interesting possibility for a long refractor is to place it horizontally and bring light into the objective through use of a coelostat or a siderostat. The latter results in a rotating image. It is important to mount this type of instrument well above ground air currents. You must place the mirrors far enough in front of the objective that they can be directed behind the telescope in its sky coverage.

—Robert E. Cox

Letters

there is the matter of breakage and bad glass. Breakage rates of 10% are not uncommon, especially when working with this fragile material. Bad glass is even a worse problem. If you specify that the glass meet tight homogeneity and striae specs, it will cost almost as much for two blanks as the finished product. Therefore, you will have to accept grade B material. While modern optical glass is generally very good, sometimes it can be extremely bad. Our experience with United Lens and Schott is that you usually find 30% of a batch to be absolutely unusable. Their specs allow an index variation of 0.0001 across the blank. For those amateurs who have lens design problems, try varying the index of one of your elements by this amount. You will be shocked and amazed by the result.

Japanese glass is generally of more uniform quality. Their tolerances are tighter, with index variations of 0.00002. This much variation will still make a poor lens. Therefore, in production we can expect to lose up to one-third of the raw material due to breakage and poor glass.

My own feeling is that an optical system is really worthwhile only if it can be purchased by the average amateur and remain a lasting value. I have little confidence in fluoride at this time. I will of course continue to explore alternatives. I have triplet designs that have color correction equal to or better than the Gregory doublet. If we can make them at affordable prices, we will certainly produce them, not as monuments to our optical skills, but for the use and enjoyment of the little guy.

Roland Christen
Astro-Physics
7470 Forest Hills Road
Loves Park, IL 61111

Big Blank Goes Begging

Dear Sir/ Over 10 years ago, I purchased a surplus 60-inch Pyrex mirror valued by the government at $20,000. I attempted to give it away to any institution that would want it, including several museums. They all had duplicate or similar mirrors in their establishments.

The 60" mirror is about f/4 or so, I guess. The surface needs resilvering since it has been sitting in a barn and there us a small chip out of one posterior edge where lightening hit it. Otherwise it is still crated and awaiting the first person with a hydraulic lift and three-ton truck that can haul it off.

Can you find a group or establishment that would want such a thing?

H.J. Lewis
3175 Dresden Road
Zanesville, OH 43701

—Here's an exceptional opportunity for an enterprising club or individual. It's a big job: I think I'll pass. (RLB)

Dewaxing Sonotube

Dear Sir/ Just a note on removing wax from Sonotube. I use a small propane torch as if it were a spray gun and "paint" the tube. Several "coats" may be needed to remove all the wax, but the whole process need not take more than ten minutes. Be sure the flame doesn't get too close to the tube and above all keep the torch moving. The wax is removed when the tube no longer appears shiny when hit by the flame.

Special thanks to Richard Mikovsky for his *TM* index, and to *TM* for printing it. I've refered to this index many times already.

Barry Greiner
6490 Lemon Street
East Petersburg, PA 17520

Third World TMs Help Each Other

Dear Telescope Making/ While your efforts to get associations in the U.S. to donate books and telescopes (see *TM#28*) to the third world are laudable, our experience (and we believe this is true of the first and second worlds as well) is that free gifts do not have quite the same value for the recipient as something he/she works towards.

Like most other amateur associations in the third world, the Association of Bangalore Amateur Astronomers (ABAA) is also very low on funds. (Most of our 120 members are high school or college students. Each of them pays Rs.12.50 (i.e. US $0.96 @ Rs.13.00 per U.S. dollar) as annual membership fee.)

Yet instead of seeking handouts from more affluent associations abroad, our members have:

1. *Learnt how to build telescopes .* Today the ABAA is the proud owner of a 9-inch Newtonian reflector on an equatorial mount, and quite a few 6-inch and 8-inch reflectors on Dobsonian mounts.

2. *Conducted 3 telescope making workshops.* Over 100 school children and over 30 school teachers -- all from semi-urban and rural parts of our state, Karnataka, have built a total of sixty 6-inch and 8-inch reflector telescopes on Dobsonian mounts.

3. *Produced inexpensive handbooks.* Intended for amateur astronomers and telescope makers, these books include: "A Guide to the Night Sky": Rs.8.00 (US $0.62); "How to Build a Telescope": Rs.8.00 (US $0.62); and "Clusters, Nebulae & Galaxies": Rs.12.00 (US $0.92). The production of these books was subsidized by a few governmental and non-governmental agencies, otherwise they would cost 100% more.

The point I am trying to make is do not give away anything free. But if you must, let what you give be do-it-yourself handbooks which will persuade the enthusiastic recipient to work from there on.

If you think our books would be useful to the countries you wish to help, please let me know. We will mail a few complimentary copies to you or the address you provide.

Ashok Dey
Association of Bangalore Amateur Astronomers
97, Xth Cross
IVth Main
Malleswaram,
Bangalore 560 003

Old Movies on Grinding

Dear Richard/ I've found several circa WWII U.S. government training films on optical lens testing and production. Topics include rough grinding and polishing techniques, pitch, abrasives (including cerium oxide), testing optics throughout production and after completion, how optical test equipment works, and extensive coverage of grinding and polishing equipment and machines reminiscent of *ATM Book 3.*

Although I have ground and polished two mirrors, I would never have attempted grinding a lens without something to demystify this art. I'm now working on a Shafer-Moksutor-Cass (*TM#29*) even though I don't have the equipment shown in the films. The production of the meniscus corrector lens is now a task which I look forward to.

If anyone is interested in these films—now copied onto four VHS format video tapes—I will sell them for $100.00 a set. This covers the cost of the tapes, copying, postage, and running around to do all this, plus a $15 profit for the D.-Boone's-dream-come-true telescope fund.

Daniel Boone
12902 Wolfey Drive
Peoria, AZ 85345

Letters

How NOT to Build an Observatory

Sirs, Mams, & Friends/ I'll admit that I did some things quite cleverly. But I sure wish I'd listened to wiser heads, and the thing the old pros tried to tell me. But frankly, I still love to use that observatory every time I visit Fort Davis.

I prefabbed the fiberglass top eleven hundred miles away from Fort Davis, here in Birmingham. I borrowed a twelve foot satellite dish from a company that manufactures them and then conned them into using it for the mold for the roof. The dish had a very slick smooth finish that we covered with a layer of wax

and then [first mistake] sprayed on a 5/8 inch thickness of fiberglass. Had I listened to *them* it would have been about 1/4-inch I thought more would be better—right? Wrong, it's the curved shape that makes a dome strong, not the thickness. Boy, that top is heavy.

The side panels are the same thickness and the whole thing is bolted together with—get this—3/8-inch bolts and 1/8-inch aluminum plates. That was mistake #2. A thin curved surface fastened with 1/8" bolts and 1/16" plates would hold together in 100 mile-an-hour winds with no problem.

The next mistake is that I built a 12-foot circular room for a 16-inch f/4.5 Equatorial Newtonian scope. That ain't enuf room folks! Boutwell's Third Law of Observatory Design is: 1 foot per inch of scope, minimum. *Do Not Argue With This Law!*

Fourth mistake: the slit is only three feet wide. Try to chase any object across the sky with a scope of this diameter for over 10 minutes! You spend your time trying to line up the tiny slit with a scope that suddenly has all the mechanical agility of Lord Rosse's Big 'Un. I'd say four feet is just about right.

Fifth Mistake. The very beautiful lower section of the building is made of natural stone that was laboriously gathered from *allllll* over the 4,000-acre Prude Ranch. (My back still complains about this one.) Did you know that it takes many hours for this stuff to cool down? The wavy air currents make beautiful psychedelic star images till about 1 a.m.

Numero sixo is the massive, rotating mechanism that splits the entrance in half. That means everyone must bend down to enter or exit. I tend to forget this at least once a night! Bonk!!

Seventh, the rollers I originally installed were hard rubber for quiet operation. Well, it was quiet, but it required two strong persons to brute force the top around. After three years of listening to Joe Lidell tell me they should have been metal, I allowed him to drag me to McDonald Observatory's workshop where in minutes he solved the problem with 4-inch aluminum wheels. (He *loves* to gloat over how you can now turn the dome with one hand.)

Number eight, don't ever leave your precious scope unattended even when there are good friends to watch over it. Take it home each trip. Someone always wants to clean the mirror or collimate the optics. You'll be in for some surprises when you see how they done it.

Well, everything's not so bad. In my never-ending quest efficiency, I've invented the Boutwellian mount for my wide-field Schmidt-Newtonian. The mount is an alt-alt-az-and-sometimes-equatorial.

Parts list: one toolbox or suitcase, one 1/4-20 bolt, two 1/4-20 nuts, two washers, one towel, one car hood (or other handy flat surface).

Drill one 1/4-inch hole in top of the suitcase (don't let your better half see this operation). It might be best to drill your tool kit top instead, besides there are more props for altitude adjustment such as screwdrivers, wrenches, etc.

Ed Boutwell
Route 1 Box 41-B
Columbia, AL 35051

Very Enthusiastic Reader

Dear Mr. Berry/ My back copies of *TM* arrived end of last week, for which many thanks. Your mag is even better than I expected from the few numbers which I had seen previously, twenty-eight glorious mags all of them bung full to the brim with nattering about one of my favorite pursuits. Oh rapture, Oh Joy! What sweetness does your labour bring forth! Many thanks.

By the exercise of desperate self-control have refrained from diving in and reading them from the first page of No. 1 right thro' to the last page of No. 29 in one grand glorious session of indulgence and mental indigestion like an urchin loose in a Gob-Stopper factory but certain points have even now come up for comment.

(i) The "Pretoria" coma-correcting eyepiece. Corklino, do make a habit of turning the world on its ear at your office? Took my spare copy of No.29 down to the Club workshop last night together with several Zerox copies of the Pretoria write-up and it caused chaos. Any future manufacturer has several orders all ready and waiting here in Brummagem from Day One. You never heard such a load of excited nattering or such sounds of frustrated avarice. An approach is to be made to the full committee for an in-principle approval to purchase sight unseen for the 22-inch Portadob our group is working on. Congrats to Mr. Cox on the most fruitful bit of stirring since silver on glass.

(ii) Bob Kestner's series on thin mirrors. It was only by good fortune and not without pain and bloodshed I found these articles, for your journal is as scarce as pigs in Palestine over here. I managed late last year to photocopy all three parts and read and re-read them during the winter. Correction, I did so when they were not out on loan or copy to my fellow telescope nuts. My opinion, which is shared by many, is that this paper is a remarkable contribution to telescope making lore in general and an unrivalled one on thin mirrors. Every page bears the stamp of authority; my own limited exposure to this specialized genre enables me to recognize a work from the pen of a master.

Now that I have all issues of *TM*, I'll confess: I am an idiot. All my friends tell me so, often. Might have known that Bob would have gone into print with ideas about mounting and using Dobs as well as making the mirrors. It is an even better one to get him to write a great hairy book about the subject! (Hint, Hint!)

(iii) Very interesting letter (*TM#18*, p. 41) from Sherman Schultz—but

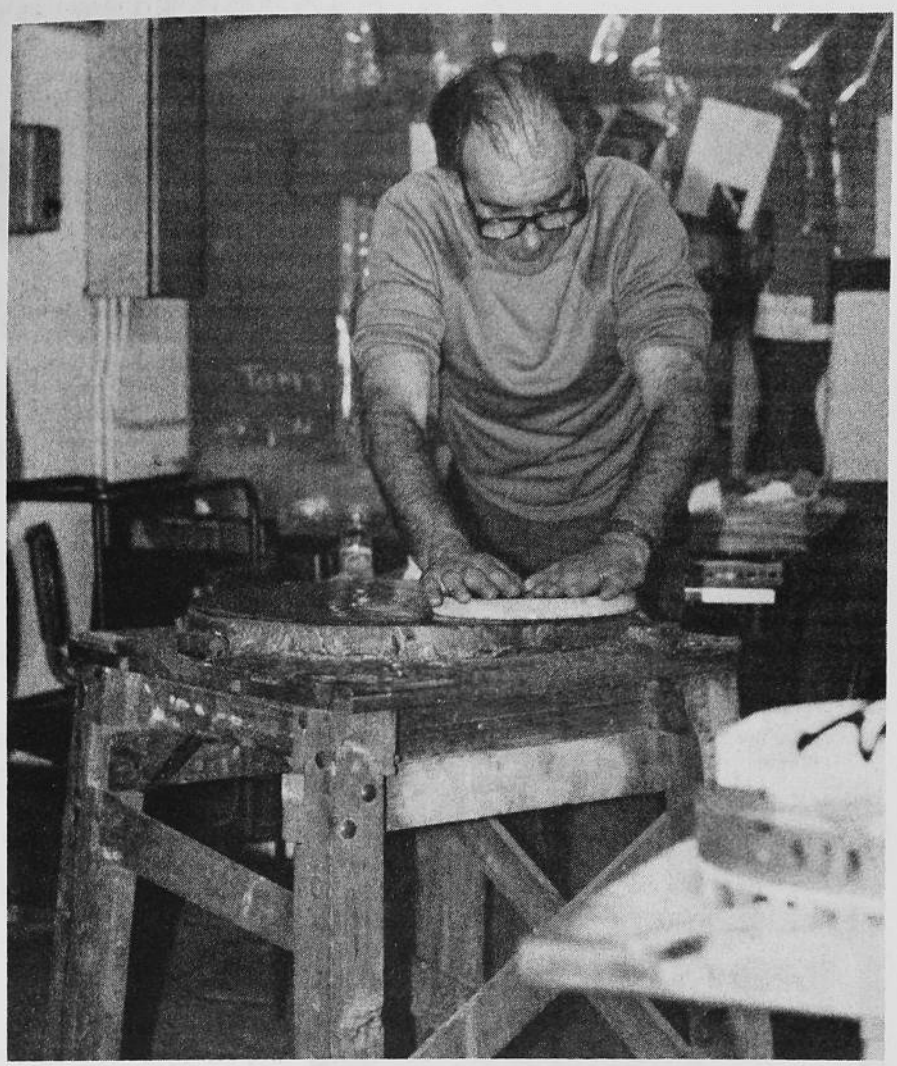
no follow up. Assuming that it is not a leg-pull, then: (a) I have not yet found the further report, (b) the project is held up due to outside events, change of circumstances etc. Large telescope efforts, and this is a very large effort, are peculiarly vulnerable to changes of circumstances, (c) there is some hold-up due to technical difficulties, or (d) the disc has failed in some way which may or may not be inherent in the design.

Have decided to drop Mr. Schultz a note of enquiry. The remark about the leg-pull is not made lightly. Unk Ingalls was a terrible puller of legs, especially if said leg was attached to a rather serious teenager. He caught me every time! However, as John Wall and I are maturing plans for an experimental glued-up disc the risk must be taken!

(iv) I got myself a copy of your book of telescope designs, **Build Your Own Telescope**, in the week before Christmas. It eased the customary Yuletide exasperation in a most satisfactory fashion! I would say at a guess you are a profound student of Russell Porter; your mountings have just that flair and essential "rightness" about them. Easy to visualize the shade of R. W. P. nodding approvingly as he leafs through it in some telescopic Valhalla.

My copy is currently going the rounds of the design committee of the 22-inch Portadob project, where it has attracted considerable comment, all favorable. The 6-inch Dobsonian refractor is especially admired. Again, I would guess that you have made a considerable study of the telescopes of yesteryear; that tube bears a quite uncanny resemblance to that of the old Northumberland refractor! Either that or similar problems and similar materials generate similar solutions. Anyway, a hearty congratulations on the book: sound designs, excellent description, pleasing presentation. Only problem is to get my copy back from a bunch of thievin' ratbags.

(v) I have noted so far you have a certain tendency to go in for items of historical interest. Fred Lynch, one of our older members, was as a youth a protege of John Hindle. He is full of anecdotes about J.H. For instance, did you know that Hindle, as a young man, knew Calver the famous old-timer? It has struck me that someone should try to get Fred's ramblings down on paper for posterity while there is still time as Fred is not getting any younger and anyway someone might shoot him to shut him up. F.L. being a notorious chatterbox. If I can keep him on the subject for long enough, would you be interested in a short essay on J.H. as I knew him? (As F.L. knew him, that is.) The picture Fred draws is quite unlike the normal image of Hindle as a gruff and formidable authoritarian; he seems to have been a kindly soul under that shell.



The 22-inch mirror advances steadily at the expense of all my other telescopic projects! Your book of telescope designs is still top of the pops with the construction section. Keep up the good work. Am also attaching a snap taken in the club grinding room, with old sweat F.H. smoothing off the 22-inch with No. 60 carbo. In spite of appearances, most of our mirrors are low-expansion glass.

Frank Hourigan
40 Wychall Lane
King's Norton
Birmingham, B38 8TA
England

—To answer your questions. University Optics is producing the Pretoria eyepiece. I haven't seen one yet, but Bob Cox has and he is very enthusiastic. Bob Kestner will be most pleased to hear your appreciation of his articles in TMs 12, 13, and 16, I am sure. But it would surprise me if he writes a great hairy book; he suffered a thousand agonies to write those articles for you. Thanks for your appreciation of my book. Yes, I have studied Porter carefully. You guessed well: the 6-inch refractor was inspired by the Northumberland refractor. The 6-inch f/8 reflector owes a lot to Launie's circa-1890 reflector, which he showed some years ago at Stellafane. As for Sherm's mirror, I'd hazard that "all of the above" is the correct answer. Haven't heard from him in a while, but I know he retired and may be enjoying life a bit. (Maybe he even swore off glassworking.) And yes, I'd be interested in Fred's "ramblings" about Hindle and Calver. —RLB

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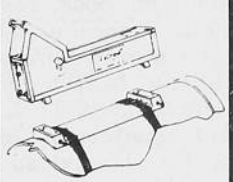

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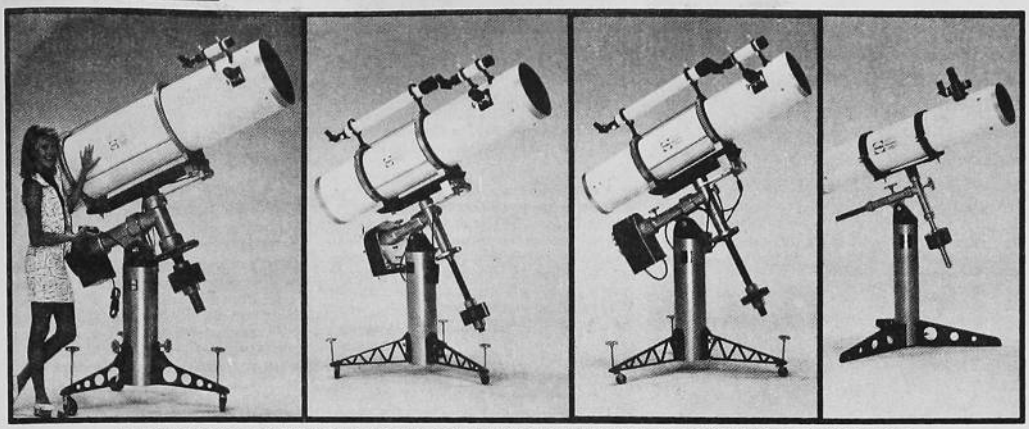

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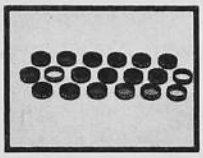

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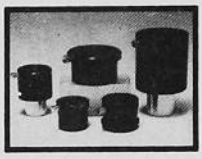

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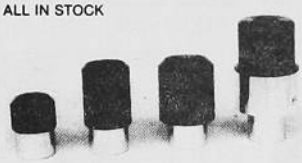

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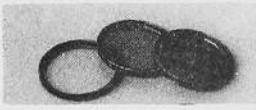

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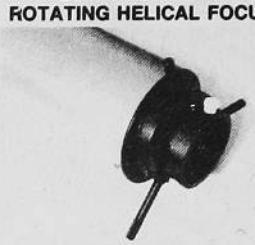

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Flat, 7" OD, 9½" OD, 12½" OD, 16" OD, 20" OD, SUPER-FINDER base plate.
LUMICON Deluxe Helical Focuser . $79.50
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2"/1¼" adapter w/48mm filter threads **$20.00**
2" LUMICON EASY-GUIDER **$139.50**

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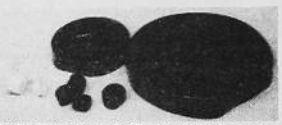

Protective plugs (left), vinyl dust covers.
Protect your valuable telescope optics, eyepieces and accessories with these black vinyl covers. Add $1 shipping. Deduct 10%, 2 or more sets.

1¼" O.D. plug, seals focuser ..... **4/$2**
2" O.D. plug . **2/$2** 3½" O.D. plug **$1.50**
1¼", 1⅜" .... **3/$2** 7½" **$8**
1½" ..... **2/$2** 9½", 10.4"* .. **$12**
2" ..... **2/$2** 12½", 12⅞"* **$15**
3½", 4½" .... **$5** 16"* **$20**
5½" ..... **$6** 19" (DS-16) .. **$27**
*Fits Odyssey

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U.S. Patent 4,473,636

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For C-8, Meade 2080, Dynamax-8. Includes 50mm achromatic lens for f/5.8 operation-3X shorter exposures! **Superb rich field viewing, too!**
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1. **Illuminated reticle eyepiece . . . $79.50**
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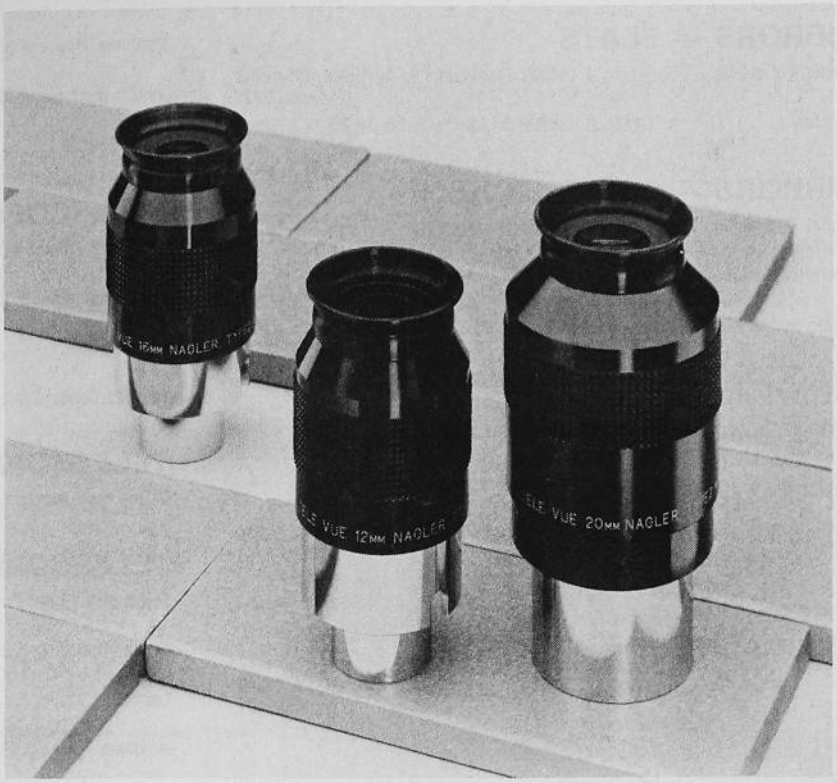
SR1600, fastest of all, color neg	24	$12.95
Konica SR200, fine grain color neg	12	$9.95
3M 1000, fastest slide film	20	$12.95
Fujichrome RD100, fine grain slide	24	$12.95
5072, color slides from neg	36	$6.95
D-19 B&W Developer	1 gal.	$6.95

Tele Vue

NAGLER TYPE 2 82° FIELD EYEPIECES



These new 8-element designs extend the Nagler concept to impressive new performance levels, while retaining the basic advances of the original Naglers:
—82° apparent field
—Full field correction
—Fast aperture correction

New Features Include:

First, three new focal lengths, 12mm, 16mm, and 20mm extend the concept to unprecedented wide viewing fields.

Second, full exit pupil correction permits comfortable night and day use.

Third, fold-down rubber eyeguards are included for maximum comfort and dark adaptation.

Fourth, relatively lightweight and moderately sized, they also have knurled rubber grip rings for easier handling.

Design Goals

The basic Nagler series has already achieved image correction 10 times better than previous wide angle eyepieces (study in "Telescope Making" titled "The Nagler 13, a Remarkable Telescope Eyepiece"). We felt that trying to extend the apparent field or image correction levels beyond that of the original Nagler series would NOT yield significant practical gains, but that extending the focal lengths WOULD offer enormous potential for spectacular low power, wide-angle viewing. After all, Tele Vue Wide-Field eyepieces have already proved the value of low power 65° viewing with important improvements in image sharpness.

What were the barriers to simply scaling up the original Nagler designs to longer focal lengths?

Two practical limits had to be overcome:

1) Substantial physical size, weight, and cost increases would be impractical.
2) Scaling up exit-pupil aberrations would be unacceptable in our judgement. Although the original Nagler eyepieces provide extremely sharp IMAGES, exit-pupil aberrations require a large (nighttime) eye pupil opening to encompass the full field. For this reason, daytime viewing with the 13mm Nagler is not recommended. Eye positioning is just too sensitive with this design to consider focal lengths longer than 13mm. The 9mm and shorter Naglers don't show this sensitivity.

Nagler Type 2: The design breakthrough!

The design experience gained in developing the patented Plössl, Wide-Field, and Nagler eyepieces resulted in an even more advanced concept: —8-element, 82° field designs (pat. pend.) with full correction of exit-pupil aberrations that permit the most comfortable viewing ever — night or day! Each model is a unique design, with a tailored eye relief like the 9mm Nagler, yet surprisingly compact, lightweight, and affordable. Extensive computer-aided design efforts and the use of new glass types retained the traditional superb full-field and fast-aperture sharpness. Of course, our pioneering lens edge-blackening, and multi-coating are included for maximum contrast.

A further important contribution to viewing comfort and effectiveness is a fold-down rubber eyeguard. This eliminates stray light and enhances dark adaptation to aid in detecting faint, delicate nebulosity and comets. The eyeguard is a delight on cold nights too.

20mm Nagler Type 2: This has the largest true field in the series, even larger than our 32mm Plössl. Yet this eyepiece, (strictly for 2 inch focusers) is comparable in size and weight to a 13mm Nagler. There's nothing like this 20mm for viewing large deep-sky open clusters, galaxies and nebulae. It gives a 4.5mm exit-pupil with f/4.5 telescopes. Daytime viewing is also simply stunning!

16mm Nagler Type 2: Offers far more true field than the 13mm Nagler, yet is similar to the 11mm in size! Great day or night performance with any telescope.

12mm Nagler Type 2: As superb as the 16mm, but with higher magnification. An excellent alternate to the 13mm or 11mm Nagler, which are preferable where the longer eye relief is of benefit to people who MUST wear eyeglasses to correct severe astigmatism.

The 16mm and 12mm TYPE 2 NAGLERS also work beautifully with Tele Vue Barlows. They both have 1¼" barrels that are parfocal with our other eyepieces and can also be used with 2" focusers.

Tele Vue

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APPROXIMATE MAGNIFICATIONS WITH TYPICAL TELESCOPES

magnifications are with 1.8x Barlows magnifications are with 2.5x Barlows

Telescope Type		4"f/5.5 Renaissance	6"f/5	8"f/5	6"f/8 5"f/10 (C-5)	10"f/6 13"f/4.5	8"f/10 (C-8)	11"f/10 (C-11)
Telescope F.L. Inches		21.6	30	40	50	60	80	110
F.L. mm		550	762	1016	1270	1524	2032	2794
Barrel Diameter 2"	Type 2 Nagler Eyepiece F.L. 20mm	Power 28x	38	51	64	76	102	140
1¼"-2"	16mm	34 62 86	48 86 119	64 114 159	79 143 198	95 171 238	127 229 318	175 314 437
1¼"-2"	12mm	46 83 115	64 114 159	85 152 212	106 190 265	127 229 317	169 305 423	233 419 582

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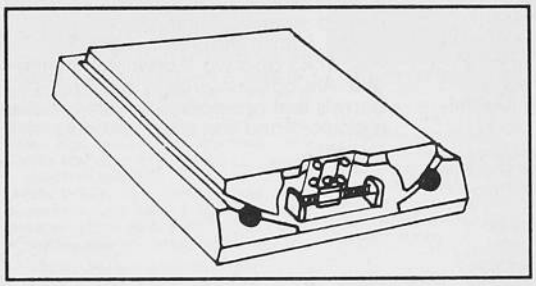

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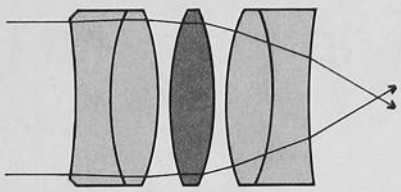
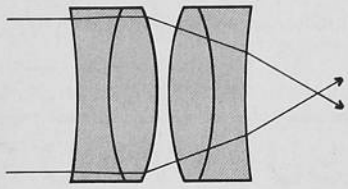
In 1984, Meade engineers set out to design the finest eyepieces and Barlow lenses—bar none—ever made available for modern telescopes. Specifications called for an unprecedented order of sophistication. Computer optimized design. Special low dispersion glasses (some not even available until recently). And the very latest in coatings technology. Not surprisingly, the resulting Meade Series 4000 is nothing less than a new performance standard in professional optics. The eyepieces and Barlows you would expect from the World's leading manufacturer of astronomical telescopes for the serious amateur.

Design Specifications: Meade Series 4000 eyepieces yield the widest possible fields of view, consistent with pinpoint edge-of-field sharpness and long eye relief, and yet with extremely low astigmatism, spherical aberration, and off-axis color. Incorporating 7-layer multi-coatings and edge-blackened optics for optimal image contrast, these sophisticated 5- to 8-element designs permit levels of optical corrections virtually impossible to achieve with eyepieces of fewer elements. The polished chromed-brass barrels are threaded for standard filters, and, where practical (see table), eyepieces and both Barlow lenses are parfocal, allowing eyepiece interchangeability without refocusing.

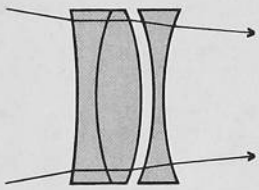
Eyepiece Groups: Eighteen focal lengths in the three Series 4000 eyepiece groups permit precisely the right eyepiece for any application. Whether your telescope is an f/4 Newtonian, an f/10 Schmidt-Cassegrain, or an f/16 refractor,



Meade 5-element Super Plössl design: the central lens element enables significant reductions in chromatic aberration and edge-distortions over other premium Plössl designs.



Other premium Plössls: include only the traditional 4-elements.



Meade Series 4000 Barlows: 3 elements, air-spaced, instead of the standard 2 non-air-spaced elements.

Series 4000 Eyepieces and Barlows

Super Plössls (5-elements)	APPARENT FIELD	BARREL DIA.	PARFOCAL
6.4mm	52°	1¼"	Yes
9.7mm	52°	1¼"	Yes
12.4mm	52°	1¼"	Yes
15mm	52°	1¼"	Yes
20mm	52°	1¼"	Yes
26mm	52°	1¼"	Yes
32mm	52°	1¼"	Yes
40mm	44°	1¼"	No
56mm	52°	2"	No
Super Wide Angles (6-elements)			
13.8mm	67°	1¼"	Yes
18mm	67°	1¼"	Yes
24.5mm	67°	1¼"	Yes
32mm	67°	2"	No
40mm	67°	2"	No
Ultra Wide Angles (8-elements)			
4.7mm	84°	1¼"	Yes
6.7mm	84°	1¼"	Yes
8.8mm	84°	1¼" & 2"	Yes
14mm	84°	1¼" & 2"	No
Barlow Lenses (3-elements, air-spaced)			
#140 2X Telenegative Amplifier		1¼"	Yes
#142 2.8X Telenegative Amplifier		1¼"	Yes

Meade 2" Mirror Diagonal: For attachment to Schmidt-Cassegrain telescopes, the 2" Mirror Diagonal permits use of Series 4000 eyepieces with 2" barrels. The 1/10-wave-flat Pyrex mirror, manufactured at the Meade Costa Mesa optical facility, is multi-coated with enhanced aluminum for maximum reflectance. An adapter for 1¼" eyepieces is included.

Where To Buy: Meade Series 4000 eyepieces and Barlows are available from over 600 authorized Meade dealers in the U.S.A. and Canada. Call us toll-free (see below) for your nearest dealer.

Meade®: First in Eyepieces too.

its performance will benefit by using these incredible oculars:

Super Plössls: With 5 optical elements rather than the traditional 4, Meade Super Plössls provide a 40% improvement in corrections for chromatic aberration and edge-distortions over any other premium Plössls. Best for general observing at moderate cost, the Super Plössl eyepieces are perfect optical complements for the Series 4000 air-spaced Barlows, below. Try the 56mm on your 8" Schmidt-Cassegrain for an actual field of over 1.4° at 36X!

Super Wide Angles: These 6-element eyepieces, with their 67° fields, offer exquisite wide-angle images at low to medium powers, ideal for star fields, galaxies, and other deep-space phenomena. Focal lengths with 1¼" barrels yield extremely high-resolution, high-power lunar and planetary images when combined with one of the Series 4000 Barlows.

Ultra Wide Angles: The ultimate in modern eyepieces, Meade 8-element Ultra Wide Angles permit extreme image fidelity and sharpness over an amazing 84° apparent field: for moderate to high power applications, no other eyepieces come close. A magnificent optical match with Schmidt-Cassegrains and fast Newtonians.

Series 4000 Barlow Lenses: The most sophisticated Barlows ever developed for commercial telescopes, these 2X and 2.8X Telenegative Amplifiers include 3-element, air-spaced, multi-coated optics, unmatched in image resolution and color correction. Both models optically complement the Series 4000 eyepieces, while significantly enhancing the performance of other eyepieces as well.

Prices: Notwithstanding their performance standards and optical sophistication, Meade Series 4000 eyepieces and Barlows are priced very competitively with other premium oculars and Barlows.

Warranty: All Series 4000 systems are covered by the Meade Limited Lifetime Warranty—the most extensive in the industry. See the Meade catalog for details.

New 1986 Meade General Catalog 86-R: $3.00

Just-published, the new Meade 1986 General Catalog includes complete information on the full range of Meade astronomical products, along with a supplement on **"How To Choose Your Eyepieces."** Send $3.00 for your copy.

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